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AUG 19 1952

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RESEARCH MEMORANDUM

SOME CONTROL CONSIDERATIONS FOR RAM-JET ENGINES

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RESEARCH MEMORANDUM

SOME CONTROL CONSIDERATIONS FOR RAM-JET ENGINES

By Seymour C. Himmel

SUMMARY

Control requirements and parameters were determined from calculated engine performance maps for a fixed-geometry ram jet of a configuration suitable for strategic supersonic missile propulsion. Several control schemes for attaining desired engine performance and for stabilizing missile flight velocity during cruise are presented.

For engine operation at minimum specific fuel consumption, critical diffuser flow conditions must be maintained. This mode of engine operation may be attained by regulation of diffuser exit Mach number with flight Mach number according to a predetermined schedule through a closed-loop fuel control or by the use of an "optimalizing" control that maintains maximum diffuser pressure ratio irrespective of flight Mach number.

Regulation of missile cruise velocity may be obtained by use of a thrust control system in which the engine fuel flow is varied as a function of flight Mach number or by means of an aerodynamic control system, sensitive to flight Mach number, which causes the missile either to dive or to climb in order to increase or to reduce velocity, respectively. The nature of missile response under such control action is presented.

INTRODUCTION

The ram-jet engine offers great potentialities as a propulsion system for supersonic guided missiles because of its simplicity of construction, low specific weight, and economy of operation. The realization of the potential of this power plant is highly dependent upon the development of engine control systems capable of maintaining proper engine operation.

A propulsion system control is, in general, required to perform two basic services; these are (1) to maintain desired engine performance throughout a flight plan, and (2) to minimize departures from desired performance during transients resulting from external disturbances acting on the engine-aircraft system. This second element, which exists for all engine-aircraft systems, assumes greater importance for the supersonic ram jet because engine performance is greatly affected by flight velocity.

In order to analyze the control requirements for a supersonic ram-jet engine, an investigation was made at the NACA Lewis laboratory of the performance of a fixed-geometry ram-jet engine of a configuration considered representative of those desirable for the propulsion of strategic guided missiles. From the computed performance maps thus obtained it was possible to select engine variables suitable for use as control parameters for obtaining certain modes of engine operation. Several control schemes utilizing the selected variables are presented and the advantages and disadvantages of the different schemes are discussed. The second phase of the study is concerned with the interrelation of the ram-jet propulsion system and the aircraft it propels and is concerned with the stabilization of the flight velocity of the engine-missile system. Two methods of stabilizing flight velocity are proposed and the character of the system response to external disturbances is presented. For both elements of this investigation, the principles of operation of these controls, rather than detailed design considerations, are discussed.

METHOD OF ANALYSIS

Engine configuration. - The ram-jet configuration selected for this study is shown schematically in figure 1. This configuration was designed to cruise at a flight Mach number of 3.0 and incorporates a spike-type diffuser. At the design point the ratio of diffuser capture area to combustion chamber entrance area A_0/A_2 is 0.786, which yields a combustion chamber entrance Mach number of 0.199 at design flight Mach number and an engine total temperature ratio of 2.2. (The symbols used herein are defined in the appendix.) The exhaust nozzle is of the convergent-divergent type with a contraction ratio A_5/A_4 of 0.556 and expands to combustion chamber diameter at the exit. The ratio of engine length to combustion chamber diameter is 6.0. The moderate value of the engine temperature ratio at the design condition is in accordance with the requirements of high engine efficiency for strategic missile applications.

Assumptions and method of computation. - The diffuser pressure recovery characteristic assumed for the performance calculations is shown in figure 2, where maximum diffuser pressure recovery is plotted as a function of flight Mach number for a fixed diffuser geometry designed for a flight Mach number of 3.0. The recoveries indicated compare favorably with those achieved by fixed-geometry single cone diffusers in this Mach number region.

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At a given flight Mach number and altitude, specifying the engine temperature ratio defines the internal performance of the engine. One-dimensional flow relations were used in computing the internal performance of the engine. The pressure drop across the flame holders was assumed equal to two combustion chamber entrance velocity heads. $2q_2$ For subcritical engine operation, that is, for the diffuser operating at less than the maximum mass flow ratio, it was assumed, for simplicity, that the diffuser pressure recovery was constant at the maximum attainable at the given flight Mach number. For each value of temperature ratio the net thrust, diffuser pressure ratio P_2/p_0, diffuser exit Mach number M_2, fuel flow W_f, and fuel-air ratio were determined. Effective values of fuel flow are used throughout rather than absolute values, which are a function of combustion efficiency. The effective fuel flow is defined as the product of actual fuel flow and combustion efficiency. The fuel characteristics assumed are those of a typical hydrocarbon fuel.

The external characteristics of the engine considered were the additive drag, friction drag, and cowl pressure drag. The additive drag was computed according to the method presented in reference 1. The friction drag was computed using the flat-plate formula of reference 2, which assumes the temperature of the boundary-layer air to be the arithmetic mean of the wall and the free-stream temperatures, and was increased by 5 percent to account for the effect of body geometry on friction drag coefficient. The diffuser cowl was assumed to have a lip angle of 6° and an external length of approximately 0.6 combustion chamber diameters. Cowl pressure drags were estimated from two-dimensional and conical flow considerations. The sum of these drags was subtracted from the net internal thrust to yield what is designated the propulsive thrust F_p of the engine. From the propulsive thrust and the engine effective fuel flow, the specific fuel consumption of the engine was computed.

Engine performance was computed for Mach numbers from 2.6 to 3.4 for altitudes above 35,000 feet. Again, the range of conditions selected for the computations is in accord with conditions considered desirable for long range ram-jet powered missiles.

RESULTS AND DISCUSSION

Engine Performance

The calculation of engine performance indicated in the preceding section provides sufficient data for the preparation of the performance charts shown in figure 3, where engine propulsive thrust is shown as a function of corrected effective fuel flow, engine total temperature ratio, diffuser pressure ratio, and diffuser exit Mach number for a range of flight Mach numbers. Both propulsive thrust and effective fuel flow have been corrected by combustion chamber area to make the charts applicable to any size engine of this configuration and by ambient static pressure to generalize the variables for the effect of altitude pressure in the isothermal region of the atmosphere. Reynolds number effects are neglected in such a generalization. 2570

At any flight Mach number the thrust curves show certain basic characteristics. As effective fuel flow or temperature ratio is increased, thrust increases rapidly as does the diffuser pressure ratio. At the critical point, maximum mass flow through the engine and maximum pressure ratio are attained, and at this point a discontinuity occurs in the slope of the thrust curve. Beyond this point the propulsive thrust increases only slightly with increasing engine temperature ratio or fuel flow; such engine operation is termed subcritical and may be accompanied by a diffuser flow instability termed "pulsing" or "buzz" (reference 3).

The variation of thrust specific fuel consumption with effective fuel flow and thrust is shown in figure 4 for several flight Mach numbers. It can be seen that minimum specific fuel consumption occurs at the point of critical diffuser flow (fig. 3) and that the increase of propulsive thrust obtained by operating in the subcritical region is accompanied by large increases in thrust specific fuel consumption. Supercritical operation, that is, operation at reduced pressure recoveries and thrust, also yields increased values of specific fuel consumption, but there is a region near the critical point where only a slight reduction in engine efficiency occurs.

How about Enable

In order to achieve a specified range with minimum missile weight it is desirable to operate a ram jet at its point of minimum specific fuel consumption, for at this point not only maximum engine efficiency but also almost maximum thrust is attained at a given flight Mach number. As indicated by the preceding performance curves, this condition of minimum specific fuel consumption occurs at the critical diffuser condition and thus establishes a possible control requirement for long range missile configurations; that is, the control must maintain critical diffuser flow.

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Control Relations

It can be seen that the basic control considerations for the ram-jet engine operating at supersonic flight speeds are inherently concerned with the characteristics of the inlet diffuser. In effect, the control problem for the ram jet may be resolved into the determination of the method of manipulation of the input variable to attain satisfactory diffuser and hence engine performance.

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The fixed-geometry ram jet has but one input variable which can be manipulated to obtain the desired engine operation - this variable is engine fuel flow. The effective fuel flow required for critical engine operation is shown in figure 5 as a function of flight Mach number. The fuel flow for this mode of engine operation (minimum specific fuel consumption) increases exponentially with flight speed and varies threefold over the range of Mach numbers shown. In order to maintain critical operation of the engine, it is, of course, possible to schedule the corrected fuel flow as a function of flight Mach number; but this requires accurate knowledge of the variation of combustion efficiency during a flight plan and such a control scheme can offer no and alt. compensation positive assurance of proper engine operation.

It is advantageous to utilize some engine variable which is truly indicative of the engine operating point to control the fuel flow to the engine. Two engine parameters which satisfy this requirement and are not functions of combustion efficiency are the ratio of diffuser exit total pressure to ambient static pressure (diffuser pressure ratio) and the diffuser exit Mach number. The variation of these parameters with flight Mach number required for critical engine operation may be obtained from figures 3(c) and 3(d), respectively, and are shown in figure 6. These curves represent, in fact, possible control relations for critical ram-jet operation which can be maintained by variation of engine fuel flow; that is, the desired value of either of these parameters can be used as a scheduled function of the flight Mach number attainable by manipulation of the fuel flow in a closed-loop fuel control. The application of each of these variables in such a control system is now considered.

Control of diffuser pressure ratio. - A block diagram of a possible control system utilizing the control relation between diffuser pressure ratio and flight Mach number is shown in figure 7. In the system shown, flight Mach number is measured by a Machmeter or similar instrument and this signal is fed into a scheduler. This scheduler has built into it a computing device (such as cams or specially wound potentiometers) such that its output bears the functional relation to flight Mach number indicated in figure 6(b). The output of the scheduler is therefore the required value of diffuser pressure ratio. The value of pressure ratio existing at the diffuser exit is measured and this signal is fed back to be compared with the required value of P_2/p_0 in an error detector. Any error or difference between the required and existing value of pressure ratio acts through a fuel control to vary the fuel flow in such a manner as to bring the error to zero, thus attaining the desired operating point. This system is advantageous because it automatically corrects for the variation in ambient pressure with altitude and is not influenced by variations in combustion efficiency.

This system has, however, one important disadvantage: such a control may easily be "fooled" into placing the engine in the subcritical region with attendant loss of efficiency and possible diffuser pulsing. The manner in which this occurs can be deduced from figure 8, which presents plots of diffuser pressure ratio against effective corrected fuel flow at various constant flight Mach numbers. The plot has been subdivided into supercritical and subcritical operating regions. In the supercritical engine operating region, an increase in fuel flow results in an increase in pressure ratio; therefore if the control shown in figure 7 senses a diffuser pressure ratio less than the set value, it will act to increase the fuel flow and thus raise the diffuser pressure ratio, bringing the engine toward the critical point. At the critical point, there is a discontinuity in the pressure ratio curve; the nature of this discontinuity is a function of the diffuser characteristics. In general, there are two possible behaviors of pressure ratio in the subcritical region - the pressure ratio may have a constant value (as was assumed for the computations), or it may decrease with increasing fuel flow (as indicated by the dashed lines) with possible attendant pulsing. In either event it is possible for the control to increase the fuel flow continuously in an effort to raise the pressure ratio, and either engine failure or combustion blow-out will occur. In the case of the flat diffuser characteristic, this could be caused by an error in the control schedule, a calibration error, for example, such that a value of pressure ratio is set that is higher than the value attainable at the given Mach number. For a diffuser with a decreasing pressure ratio characteristic, any disturbance which acted to place the engine in the subcritical region could initiate the continuous increase of fuel flow. Therefore, this control scheme would be relatively unsatisfactory for critical engine operation unless some sort of fuel flow limiting device were incorporated in the system.

Control of diffuser exit Mach number. - The use of diffuser exit Mach number to control fuel flow overcomes the principal disadvantage of the system controlled by diffuser pressure ratio. The control system using this parameter is essentially the same as that shown in figure 7 for the pressure ratio system, the difference being that M_2 is measured and that the output of the schedule is related to the flight Mach number by the curve shown in figure 6(a). The system operates in a similar manner; any difference between the required value of diffuser exit Mach number and the value existing in the engine acts through the fuel control to reduce the error to zero, thus attaining the desired operating point. This system possesses all the advantages of the system controlling diffuser pressure ratio - it compensates for changes in ambient pressure and is also unaffected by variations in combustion efficiency. Furthermore, the relation between diffuser exit Mach number and fuel flow is continuous, as can be seen from figure 9, and therefore continuous increase of fuel flow cannot be caused by inadvertent subcritical operation. If the engine should get into the subcritical region, the value of the exit Mach number would be below that required for critical operation, which would cause the control to decrease the fuel flow and thus bring the engine back toward its critical point. Of course, this system could produce subcritical operation if the schedule were in error and called for a value of diffuser exit Mach number below that required for critical operation. In this event, the control would maintain subcritical operation but would not continually increase the fuel flow. The chief disadvantage of this system would appear to be the small order of the variation of the controlled parameter, variation of M_2 from 0.16 to 0.25 being sufficient to cover almost the complete range of thrust at a given flight Mach number. This would require the development of highly accurate sensing devices to measure the diffuser exit Mach number.

It should be noted that the control systems just proposed can be used to attain modes of engine operation other than critical-point operation, since at any flight Mach number there exist unique relations among diffuser pressure ratio, diffuser exit Mach number, and engine thrust. The attainment of any desired mode of engine operation within the capabilities of the ram jet requires merely the use of a different control schedule relation in the systems presented. The discussion has been limited to critical-point operation because, as previously stated, this manner of engine operation is desirable for long range missile application.

Optimizing control. - In order to attain critical operation of the engine, the controls considered have depended upon a schedule of a controlled variable with flight Mach number and as such are subject to errors and inaccuracies caused by possible variations in engine characteristics due to manufacturing tolerances and other similarly unavoidable factors. The ram-jet engine possesses, however, a property that makes possible the elimination of such sources of error and the fullest utilization of the capabilities of the engine. This property is, paradoxically, the peaks in the pressure ratio curves which were the source of difficulties in the first control system considered. The coincidence of these peaks with the point of optimum engine performance makes possible the utilization of the underlying principles of the "optimalizer" control as proposed in reference 4. Such a system will seek the point of maximum diffuser pressure ratio at all times and thus will achieve critical engine operation.

The principle of operation of this control may be illustrated by a consideration of figure 10. In this figure is reproduced the variation of diffuser pressure ratio with fuel flow at a constant flight Mach number. (The decreasing pressure ratio characteristic is shown here, for this is the most prevalent behavior of diffusers.) The control operates in the following manner: A small periodic variation in fuel flow, superimposed on the mean fuel flow, is sent into the combustion chamber. Changes in the diffuser pressure ratio P_2/p_0 result from the variation in fuel flow and the pressure ratio variations are measured and compared with the impressed fuel flow variation. If the engine is in the supercritical region, then, as can be seen from figure 10, an increase in fuel flow results in an increase in pressure ratio; for a sinusoidal fuel flow variation, the variation of the parameters with time will appear as shown in the lower left. The fuel flow and pressure ratio signals are essentially in phase. This in-phase relation between input and output is detected by a phase sensitive device; the output of the phase detector causes a fuel control to increase the average fuel flow and thereby brings the engine toward the critical point. If the engine is in the subcritical region, an increase in fuel flow will result in a decrease in pressure ratio. This condition is illustrated in the lower right of figure 10. In this region, the variation in pressure ratio is essentially 180° out of phase with the fuel flow and the phase detector output will cause the fuel control to decrease the fuel flow and therefore bring the engine back toward the critical point. The control just described is of the "on-off" type in that the average fuel flow is either increasing or decreasing and is the simplest possible type of such an optimizing system. Reference 4 discusses more refined schemes for attaining desirable optimalizing control performance. (A control of this nature, that is, an optimalizing system, is under development and is discussed in reference 5.)

This control seeks peak pressure ratio at all times and thus automatically satisfies the requirement for critical engine operation. It has all the advantages of the previously discussed systems, that is, it is independent of altitude and combustion efficiency. Under such control action, there will, of course, be the continuous variation in thrust caused by the variation of fuel flow, but this can be kept small as determined by the minimum input signal size acceptable for control purposes. One important requirement for the successful application of such a control is the existence of a sufficiently wide band of frequencies, free from noise and interference effects, on either side of the frequency of the imposed disturbance. Such a band may be difficult to find in a ram jet because combustion roughness and diffuser pulsing may produce noise of large amplitude in the diffuser pressure signal over a very wide range of frequencies.

Flight Considerations

Thus far only the considerations involved in attaining a desired engine operating point have been discussed. The interrelation of missile flight plan requirements and ram-jet performance will now be discussed. Long range missiles powered by air-consuming power plants are normally designed to cruise on the Breguet flight plan, which requires that the missile maintain constant flight Mach number. The operating map of the ram-jet engine considered in this investigation is shown in figure 11(a), in which is plotted the variation of corrected thrust with flight Mach number at several constant corrected fuel flows. These curves are cross plots of the curves of figure 3(a). The cruise flight Mach number for the system considered is 3.0 and at this point the propulsive thrust must equal the missile drag. A typical missile drag curve at constant angle of attack and essentially constant altitude is superimposed on the engine map such that cruise with critical engine operation at Mach number 3.0 is attained. Only one equilibrium point is indicated on this figure, the cruise point at Mach number 3.0. The engine map has been subdivided into subcritical and supercritical operating regions.

It is apparent that for an engine operating at constant corrected fuel flow the configuration is unstable in flight velocity; any external disturbance acting to decrease missile flight speed would place the system in a region where drag is greater than thrust and continuous deceleration would result. On the other hand, a disturbance acting to increase missile velocity places the system in a region where drag is greater than thrust and the decelerating force which exists in this region has a stabilizing effect, tending to restore the system to cruise velocity. If a control designed to maintain critical engine conditions were in operation, the engine thrust line would be that shown by the dash-dot line. Under this mode of engine operation the system is unstable for either form of external disturbance. Similar instability characteristics may be deduced from figure 11(b), which shows engine performance at constant diffuser exit Mach number. This velocity instability represents a control problem of prime importance for the cruise phase of a missile flight plan.

Two means for stabilizing missile velocity are considered: The first is to utilize available aerodynamic and gravitational forces to stabilize flight velocity. If, for example, the missile is below cruise velocity, the angle of attack may be decreased. This change in angle of attack decreases the drag and lift and places the missile in a shallow dive to increase the velocity. The second method is to vary engine thrust through fuel flow to provide a restoring force for the missile. For an engine designed to cruise at critical conditions this normally cannot be done safely, for an increase in fuel flow results in subcritical operation which may be accompanied by diffuser instability. Also, the available increase of thrust is quite small and excessively long response times would prevail. It is better to design the engine for supercritical operation at the cruise velocity which then safely provides the necessary latitude of thrust variation to stabilize flight velocity. This design, however, requires an oversized engine to propel the missile, which results in an increase in missile weight, because supercritical engine thrust and efficiency are less than those attainable at the critical point.

In order to determine the nature of missile behavior during transients when the missile is operating under controls utilizing these methods of missile velocity stabilization, the dynamics of an idealized missile-engine combination were investigated with the aid of a differential analyzer for a representative missile configuration. The drag characteristics of the airframe (minus engine nacelles) considered are shown in figure 12 as a plot of drag coefficient (based on wing area) against flight Mach number for several angles of attack. Missile weight was assumed to be 25,000 pounds, the ratio of engine combustion chamber area to wing area was 0.0269, the wing loading was approximately 92 pounds per square foot of projected wing area, and the cruise altitude was 60,000 feet. At cruise conditions the angle of attack was 3.5 degrees and the drag curve in figure 11 is for this angle of attack.

Velocity stabilization through angle of attack. - A block diagram of a possible control system for cruise velocity stabilization utilizing aerodynamic forces is shown in figure 13. Missile flight Mach number is sensed and compared with the required Mach number in an error detector. If any difference or error exists between measured and set flight Mach numbers, this error signal acts through an angle of attack control to vary the angle of attack in proportion to the magnitude of the error. The control acts to increase angle of attack for overspeed conditions and to decrease it for less than the required speed. As the missile approaches the cruise velocity, the error decreases and the angle of attack is restored to its equilibrium value. The engine control plays a relatively minor role in this system. Essentially, it should be designed to maintain maximum safe thrust (i.e., critical thrust) during underspeed conditions and a safe thrust (e.g., constant fuel flow operation) when the missile is above the required speed. As such, this can be a critical-point operation control of the type discussed previously with a fuel flow limiting device incorporated for overspeed conditions. For the missile configuration studied, the time required to change the attitude of the missile in pitch was assumed small compared with the time required to change the flight speed, and the equations of motion of the missile were solved with the dynamics of attitude changes not considered. These dynamics must, of course, be considered in the design of an actual control system.

The response of the missile considered to a disturbance in flight velocity under the action of the control system of figure 13 is shown in figure 14. Plotted are the variations of velocity and altitude with time for an initial departure from cruise velocity of minus 100 feet per second. The control considered was a simple proportional device with a gain of 3° angle of attack per 100 feet per second error in flight velocity. For this type of control action, the missile response is a damped oscillation in both velocity and altitude. The missile passes through the cruise velocity after about 1/2 minute but requires about 5 minutes before the oscillation damps to ±10 feet per second. During the initial oscillation, the flight altitude drops 4200 feet and after 5 minutes the oscillation has been damped to ±400 feet. Increasing the control gain, that is, increasing the change of angle of attack per unit error in flight speed, tends to decrease the response time and increase the damping; however, this is accompanied by an increased excursion in altitude during the first oscillation.

The control considered was a pure proportional control and is used merely to illustrate a principle of control rather than to represent optimum control design. A more elaborate system based on the same control principle using either derivative or integral as well as proportional action would probably decrease the oscillatory nature of the missile response and yield shorter response time as well. The response times involved are rather large, but are typical of aircraft velocity responses at high altitudes because such systems are characterized by high inertia and operate in a rarified atmosphere with attendant small restoring forces.

Velocity stabilization through engine thrust. - The second control system for stabilizing missile velocity during cruise requires supercritical engine operation. In order to investigate this type of stabilization, engine size was increased 19 percent so that the cruise point was as shown in figure 15. For this mode of engine operation the missile is essentially stable in velocity at cruise. For constant corrected fuel flow operation, the missile drag is greater than the thrust for overspeed conditions and a decelerating force exists which acts to restore the missile to cruise velocity; at flight velocities below cruise but above Mach number 2.8, thrust is greater than drag and an accelerating force exists which acts to restore the missile to cruise conditions. This restoring force is small, however, and the time required to return to equilibrium would be excessive. The response of the missile to a disturbance in flight velocity when the engine is operated at constant corrected fuel flow is shown in figure 16. Plotted are the variation with time of velocity and altitude for an initial disturbance in velocity of minus 100 feet per second. The angle of attack was assumed constant during the transient. The missile accelerates rather slowly and after about 7.25 minutes is within about 10 feet per second of the cruise velocity. Missile altitude varies during this time because of the change of lift with velocity and appears to approach a sustained oscillation, a limit cycle.

In order to decrease the time of response an engine thrust control may be used to increase the magnitude of the restoring force. A block diagram of such a system is shown in figure 17. The flight Mach number is measured and compared with the required value; if a difference or error exists, this error signal acts through a fuel control to increase thrust if the missile is below speed and to decrease thrust if the missile is over speed, thus producing an increased restoring force to bring the system to its equilibrium point. The use of high control gain for such a system, that is, large changes of fuel flow per unit error in velocity, can result in undesirable subcritical engine operation during a transient. In order to prevent such a condition, a limiting device may be incorporated in the control to prevent subcritical operation. Such a device could be the system considered earlier for attaining critical operation by scheduling diffuser exit Mach number with flight velocity. This system can be designed to act as a limiter rather than as a primary control and will then limit effective fuel flow to safe values during underspeed conditions. A minimum fuel flow limit for overspeed conditions is also required to prevent combustion blowout.

The response of the missile acting under such a control scheme, that is, thrust control with limiter action, is shown in figure 18 for an initial displacement from cruise velocity of minus 100 feet per second and with missile angle of attack held constant. The velocity returns to the cruise value in a nearly linear manner with a slight superimposed oscillation. About 3 minutes are required for the missile to attain cruise velocity. Missile altitude oscillates during the transient because of the change in lift with velocity and settles into a sustained oscillation of small amplitude, about ±200 feet, with a period of approximately 2 minutes. The response time of the particular system is of the same order of magnitude as that of the aerodynamic control system, but it must be remembered that the engine size is 19 percent greater than that considered previously and that maximum available restoring force was attained with the limiting control. The response time determined may therefore be considered to represent a minimum for this system. For smaller increases in engine size, the available restoring force decreases and larger response times result.

One relatively simple method for automatically obtaining a high gain control for cruise velocity stabilization is suggested in reference 6. This system operates by controlling the fuel flow to maintain a constant diffuser pressure ratio P_2/p_0. The operating map of the engine under such control action is shown in figure 19, where corrected propulsive thrust is plotted against flight Mach number at several constant diffuser pressure ratios. The system has a high degree of inherent stability and essentially needs no flight Mach number setting device, since setting a value of P_2/p_0 sets the cruise flight Mach number; however, the accurate calibration of the engine required may be difficult to attain.

The engine must be operated supercritically during cruise under this control scheme, and thus will be oversized, as for the thrust control system previously discussed. In addition, provision must be made to prevent subcritical engine operation since, as indicated in figure 19, engine thrust is not defined at constant diffuser pressure ratio in this region. Missile response under such a control scheme would be very similar to that shown in figure 18.

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The choice of a cruise-velocity control system depends upon many factors. Among these are the requirements of the flight plan, the requirements of the guidance or navigation system, and the nature of disturbances which may be encountered along a flight path. If it is necessary that missile weight be kept at a minimum in order to achieve a specified range, then critical engine operation and use of aerodynamic control for velocity stabilization are indicated. If missile weight is not critical, thrust control with supercritical engine operation during cruise offers the advantages of inherent stability and a minimum of variation in altitude. The missile guidance system may require a fast velocity response so that the missile may stay within the limits of a time-programmed flight plan. In this event, aerodynamic stabilization with high control gain appears to offer the best solution. The nature of the disturbances expected during flight plays an important role in the selection of the velocity control system. If the disturbances are slow acting and of small magnitude, either control scheme would be satisfactory. On the other hand, impulse-like disturbances of large repetition rate might cause serious reduction of range for either control scheme because of sensitivity to flight Mach number, and the loss of range during transients is an important consideration in the selection of a control system.

The selection of a cruise velocity control system must therefore be an engineering compromise based upon an evaluation of the requirements of the particular missile configuration and flight plan and the nature of the disturbances expected during the flight.

CONCLUSIONS

An analysis based on the calculated performance of a fixed-geometry ram jet of a configuration suitable for strategic supersonic missile propulsion was used to evaluate control requirements and parameters. The following conclusions were made:

1. For engine operation at minimum specific fuel consumption, the ram jet should be operated with critical diffuser conditions. Such operation may be attained by several control systems:

(a) Regulation of diffuser pressure ratio according to a predetermined schedule with flight Mach number by means of a closed-loop fuel control. This system is, however, capable of causing engine failure if the engine should get into subcritical operation.

(b) Regulation of diffuser exit Mach number according to a predetermined schedule with flight Mach number by means of a closed-loop fuel control.

(c) An "optimalizing" control system which automatically seeks maximum diffuser pressure ratio at all times. This system possesses the advantage of not requiring a schedule in order to obtain critical engine operation.

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All the systems listed are not affected by changes of altitude or combustion efficiency.

2. Any other mode of engine operation within engine capabilities may be attained with the system described in 1(a) and 1(b) by use of an appropriate schedule of the control parameters with flight Mach number.

3. When operating under a control maintaining critical engine operation, the engine-aircraft system is unstable in flight velocity. Two methods of stabilizing flight velocity are:

(a) Use of aerodynamic controls that cause the aircraft either to dive or climb, according to the difference between measured and desired flight Mach number.

(b) Use of engine thrust control through fuel flow from a control that senses flight Mach number and varies fuel flow according to the difference between measured and desired values of flight Mach number.

Mach number control by causing the missile either to dive or climb has inherently faster response in missile velocity than thrust control, but can be accompanied by large excursions in flight altitude. Thrust control normally will require cruise with supercritical engine operation; under this condition the aircraft is essentially stable, but larger engines and higher specific fuel consumption must be accepted for a given airframe.

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APPENDIX - SYMBOLS

A	area, sq ft
C_D	missile drag coefficient based on wing area
F_p	propulsive thrust, lb
M	Mach number
P	total pressure, lb/sq ft
p	static pressure, lb/sq ft
T	total temperature, °R
W_f	fuel flow, lb/hr
α	angle of attack, deg
η_b	combustion efficiency
τ	engine total temperature ratio, T_4/T_2

Subscripts:

R	required value of a controlled variable
0	free stream
1	diffuser entrance
2	diffuser exit
3	downstream of flame holders
4	nozzle entrance
5	nozzle throat
6	nozzle exit

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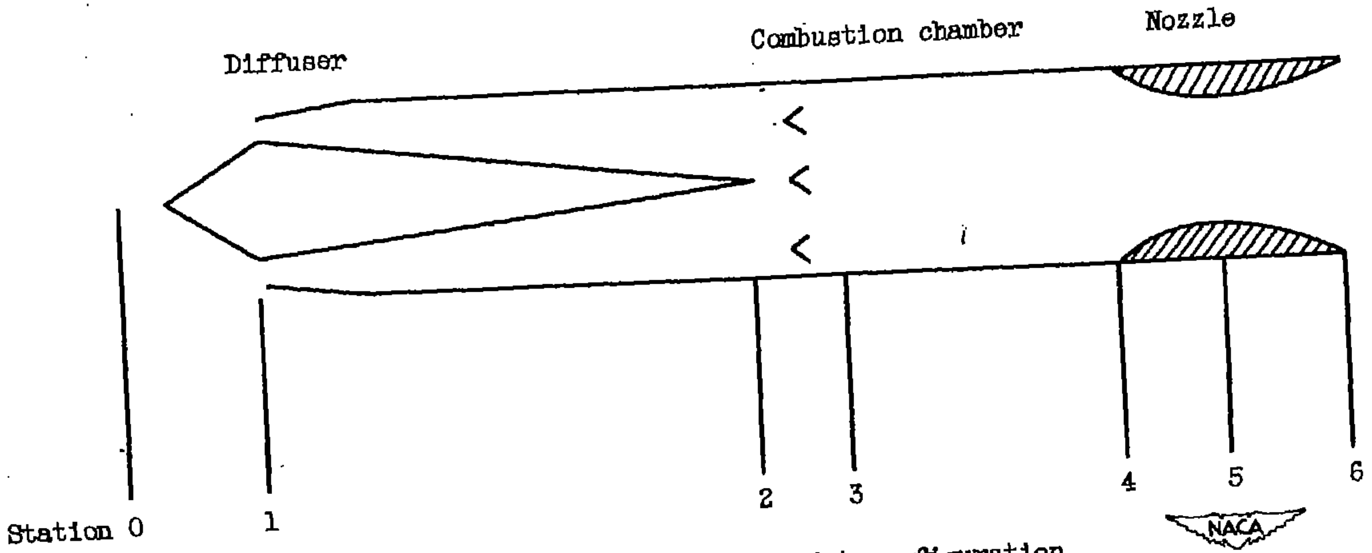

Diffuser
Combustion chamber
Nozzle
Station 0
1
2
3
4
5
6

Figure 1. - Schematic drawing of ram-jet configuration.

2570

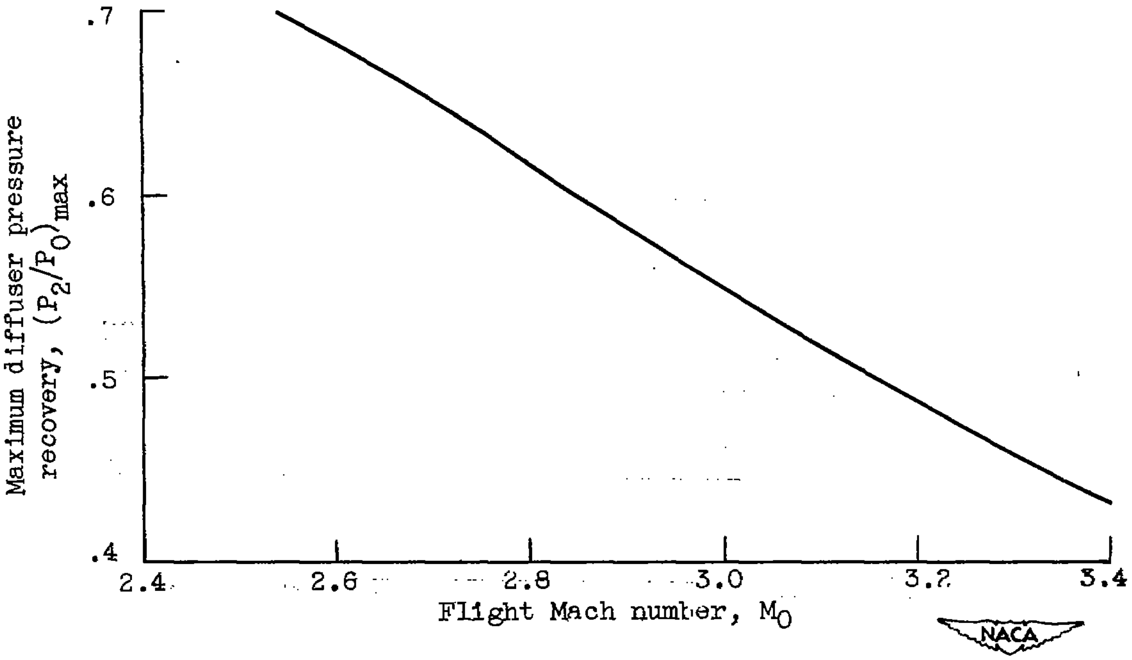
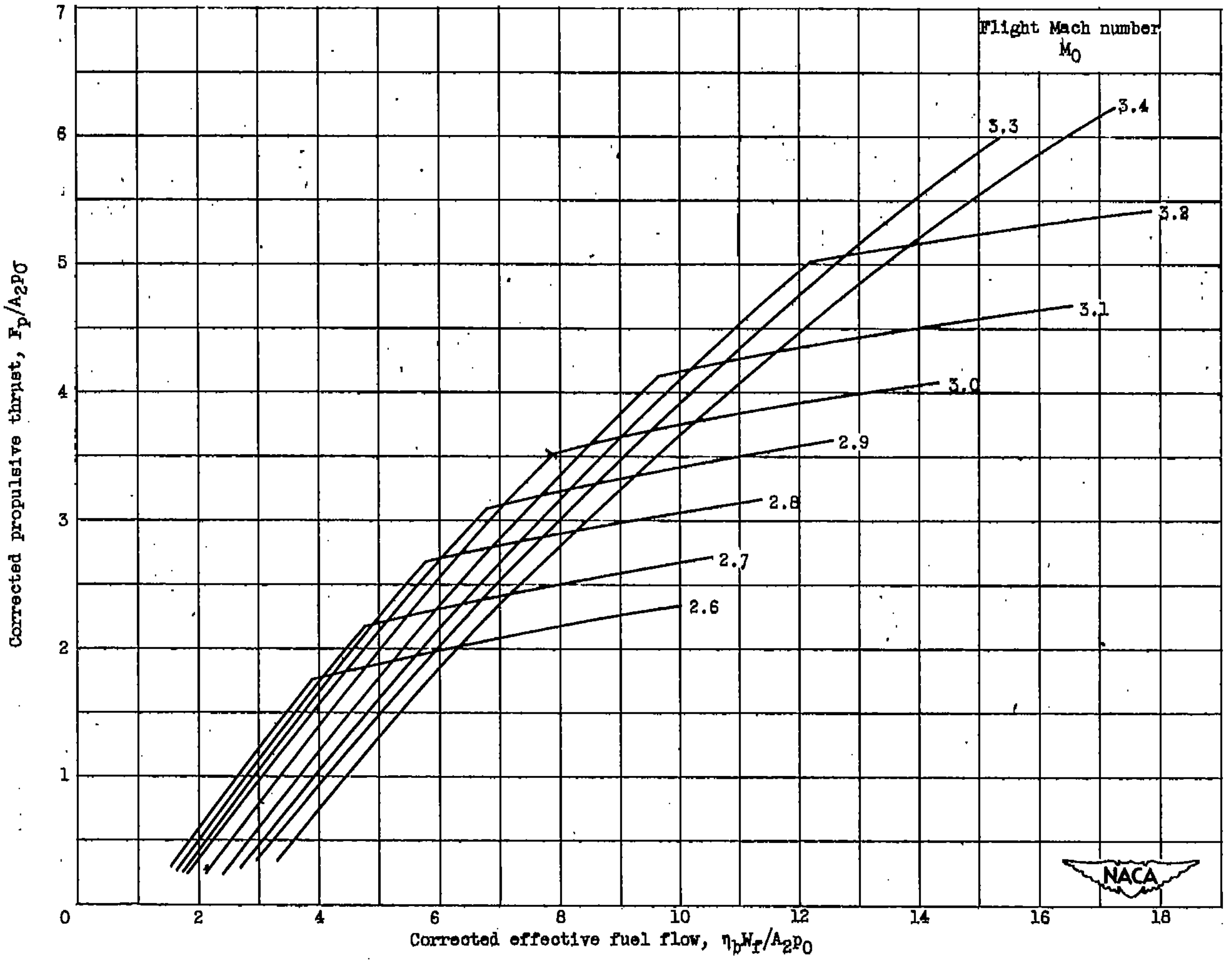


Figure 2. - Diffuser pressure recovery characteristic assumed for calculations. Fixed diffuser geometry designed for flight Mach number of 3.0.

[redacted]

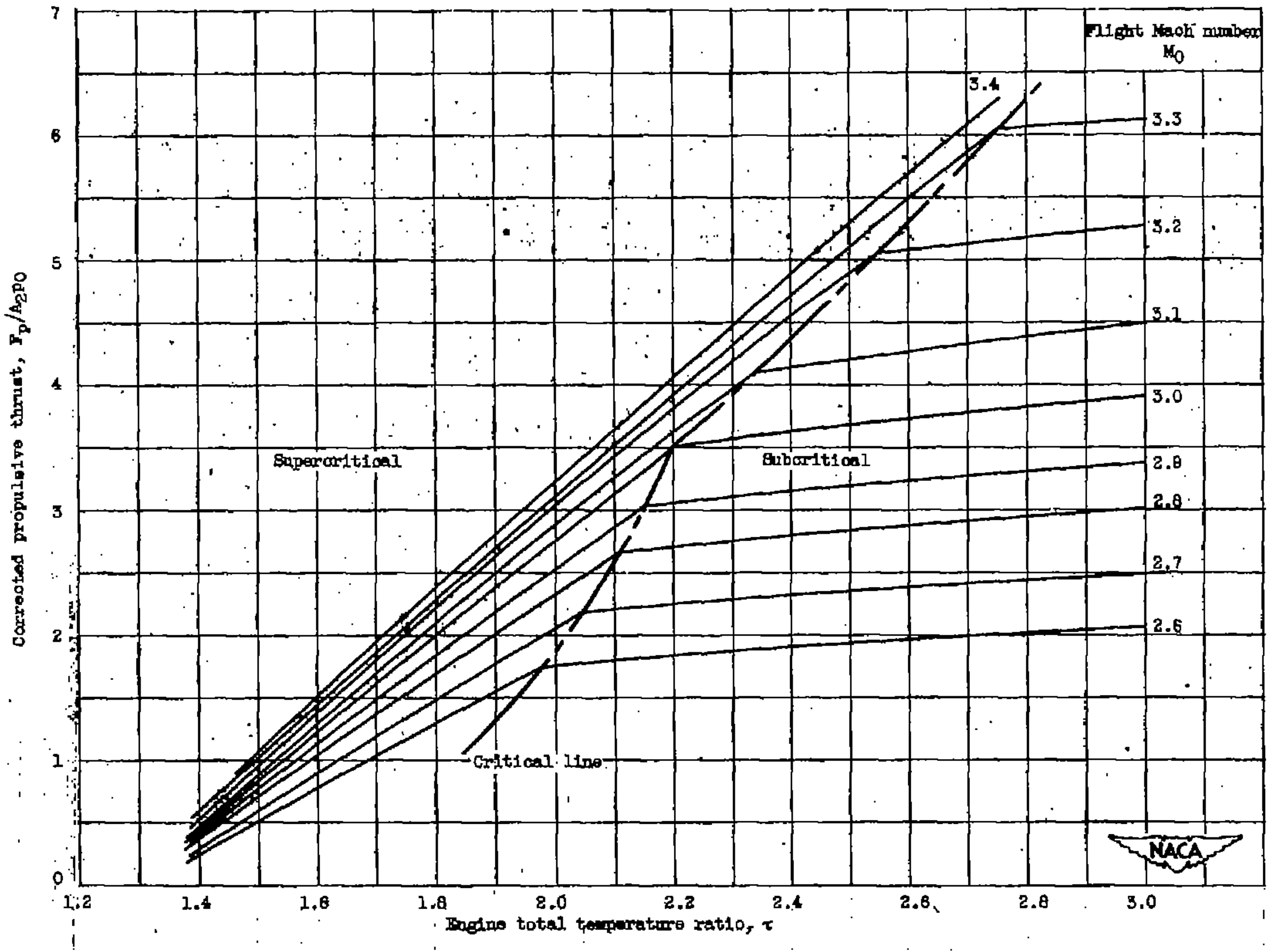


(a) Variation of thrust with effective fuel flow.

Figure 3. - Performance of ram-jet engine.

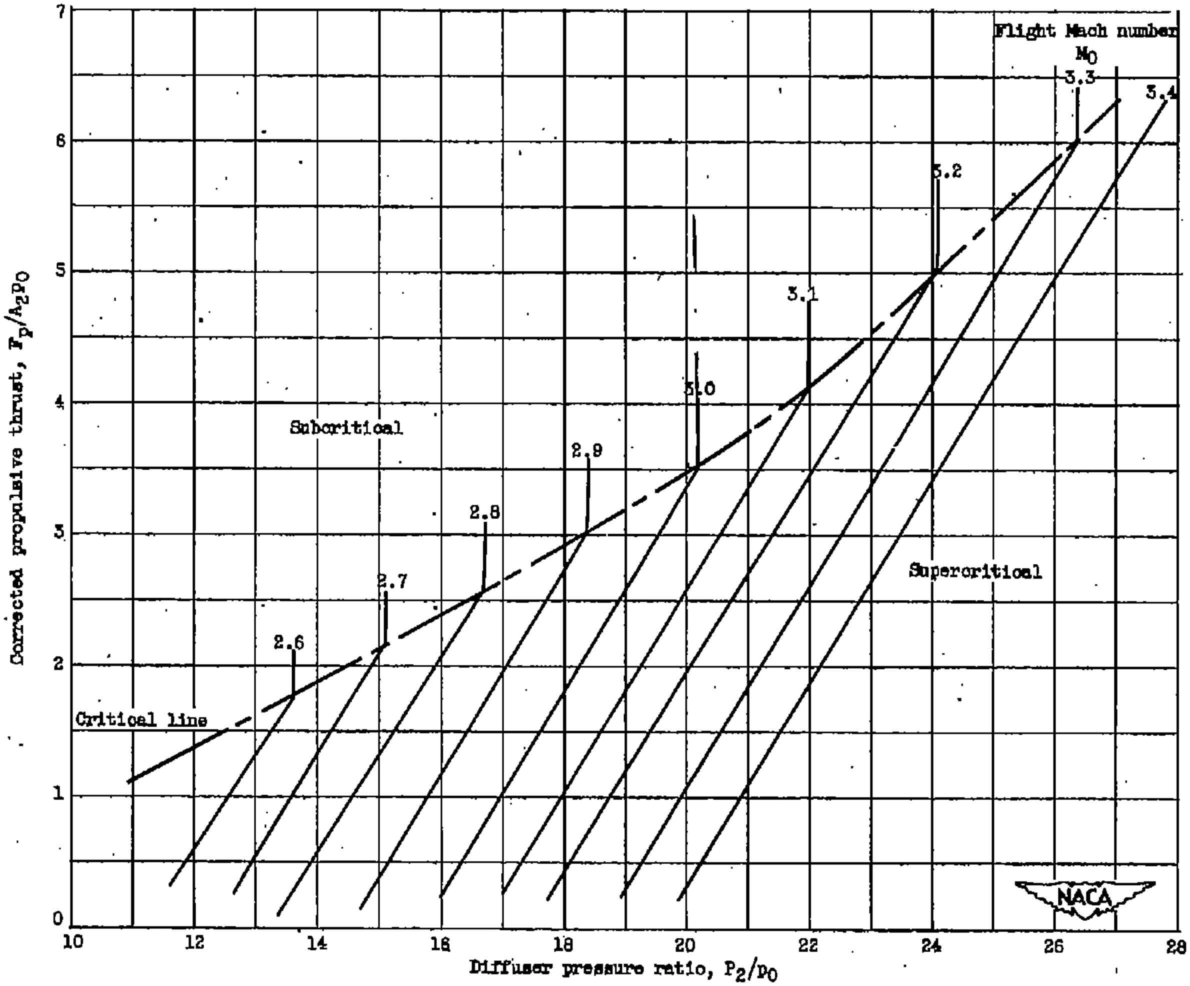
[redacted]

[redacted]



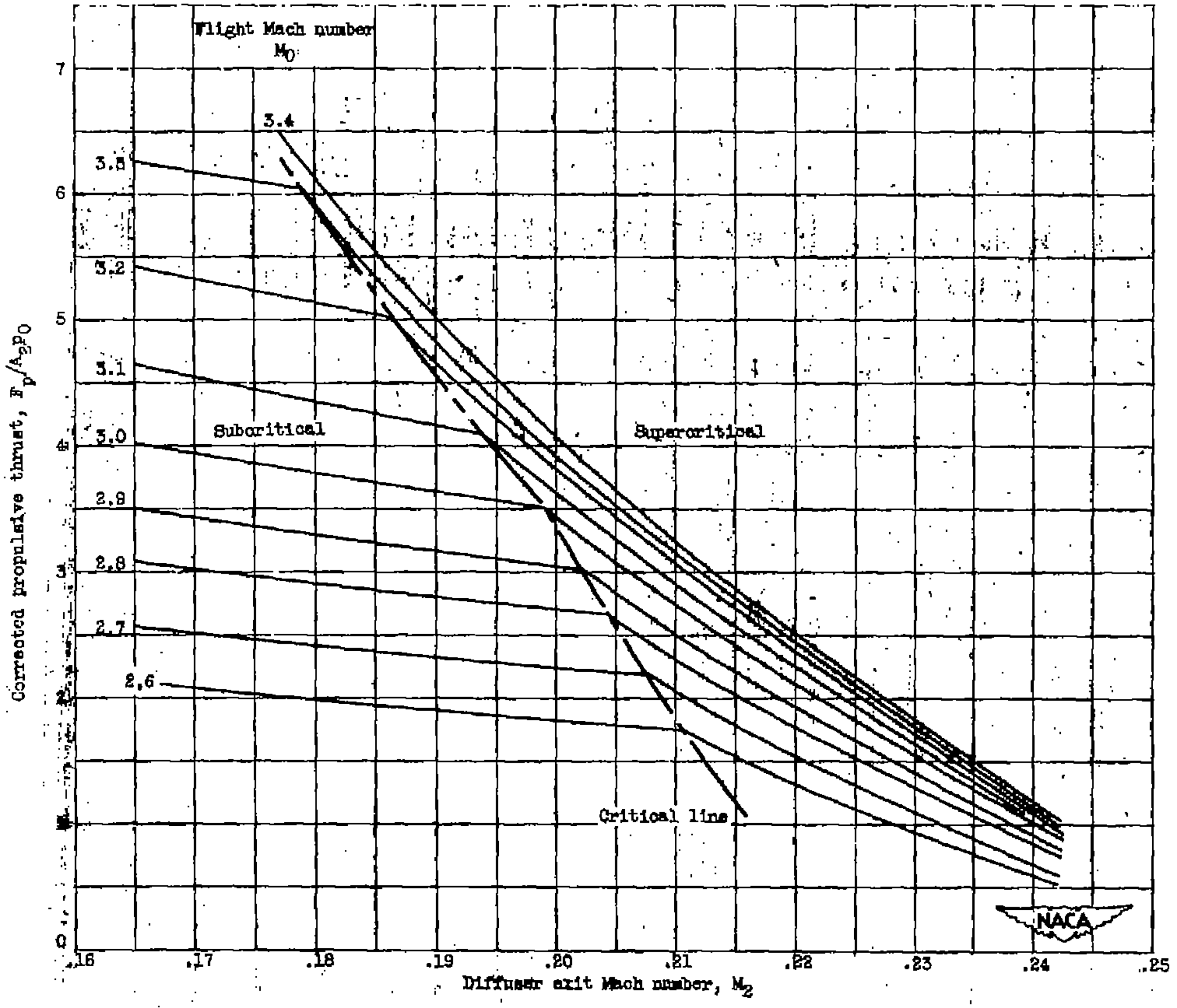
(b) Variation of thrust with engine temperature ratio.

Figure 3. - Continued. Performance of ram-jet engine.



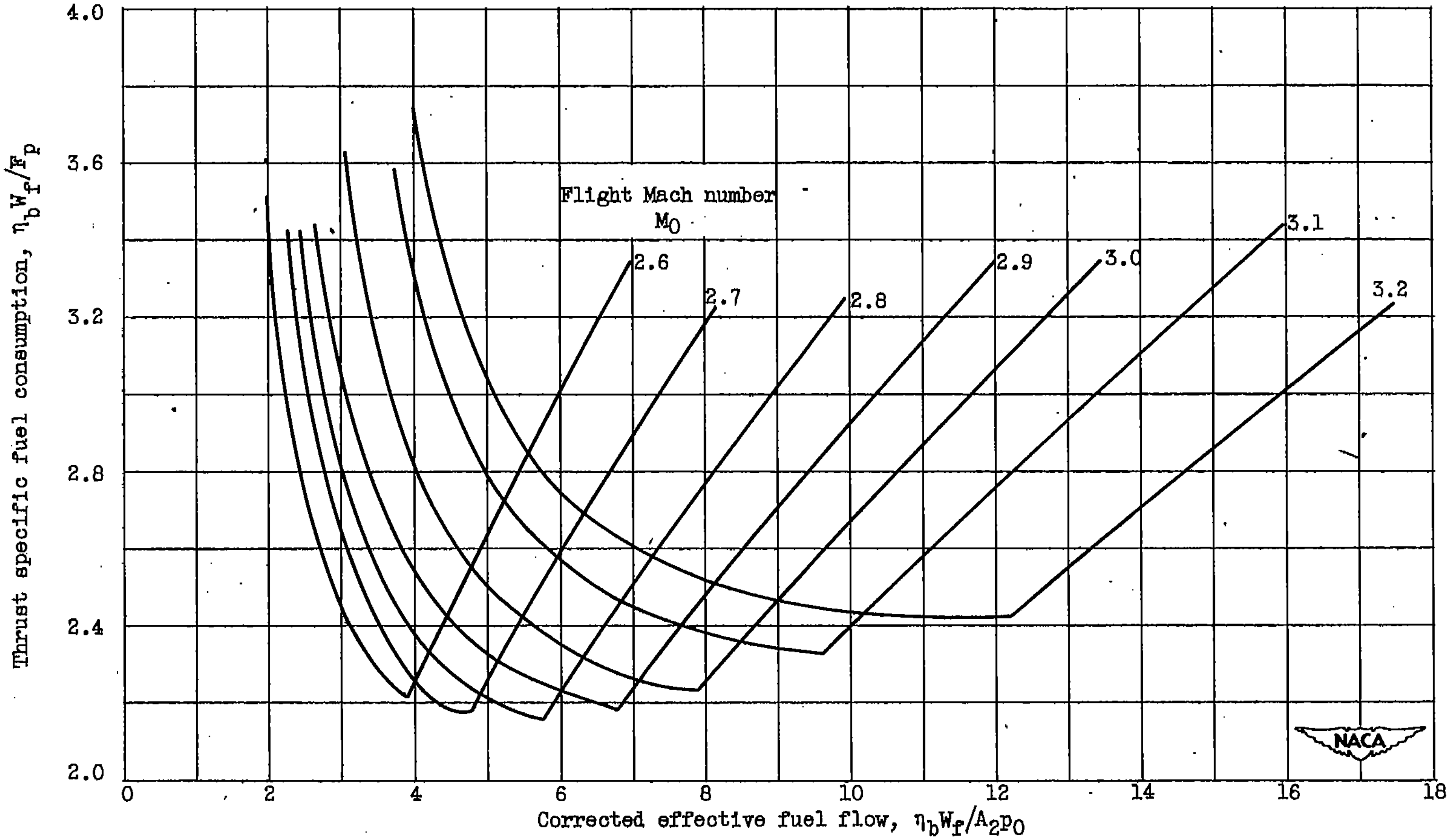
(c) Variation of thrust with diffuser pressure ratio.

Figure 3. - Continued. Performance of ram-jet engine.



(d) Variation of thrust with diffuser exit Mach number.

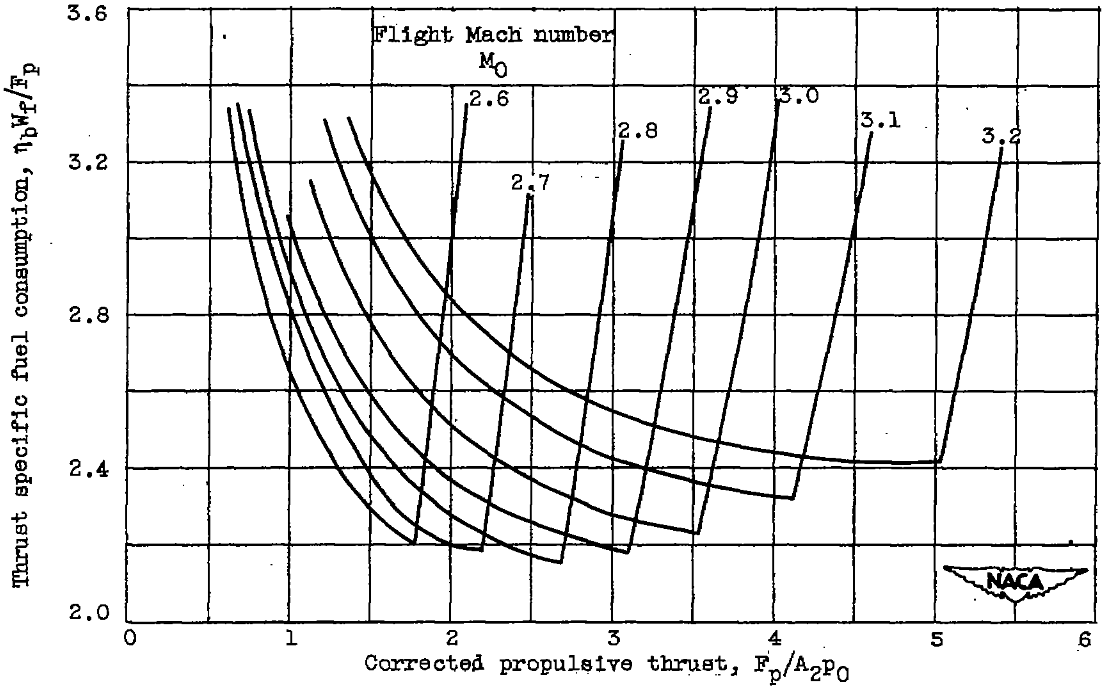
Figure 3. - Concluded. Performance of ram-jet engine.



(a) Variation of thrust specific fuel consumption with effective fuel flow.

Figure 4. - Economy of ram-jet engine operation.

2570



(b) Variation of thrust specific fuel consumption with propulsive thrust.

Figure 4. - Concluded. Economy of ram-jet engine operation.

2570

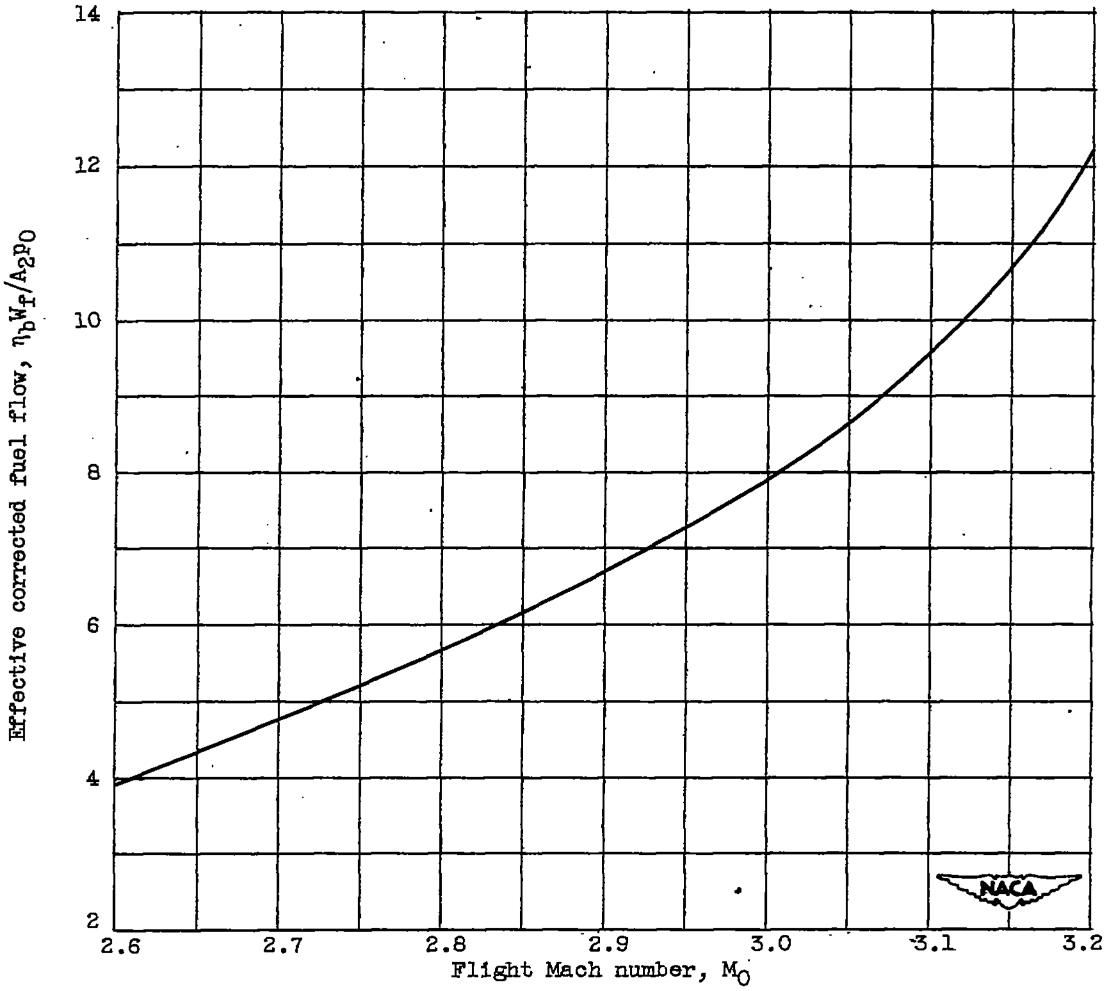
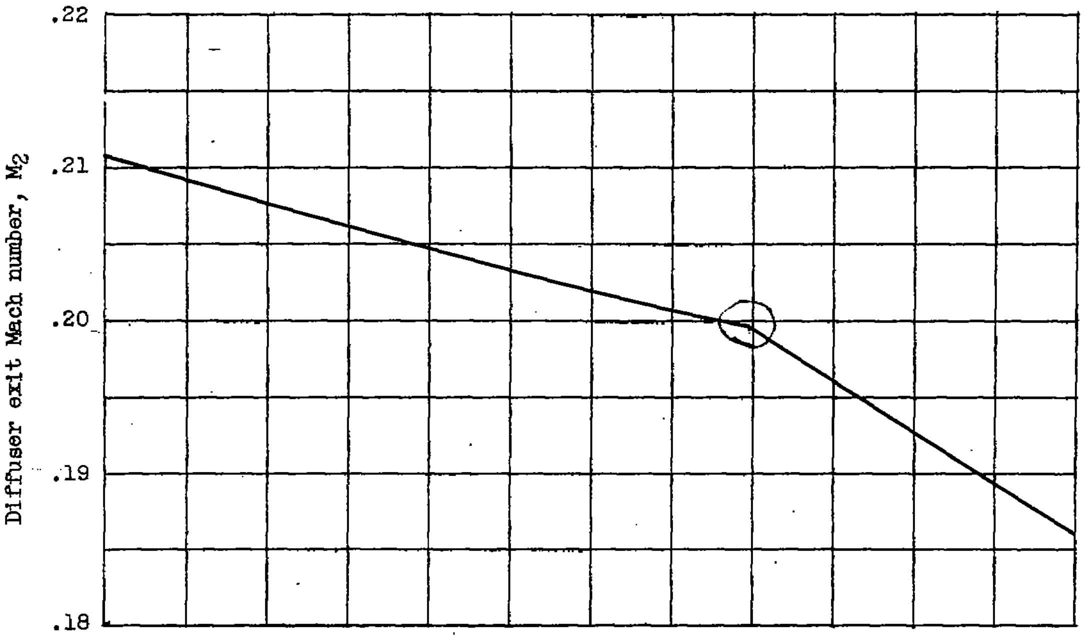
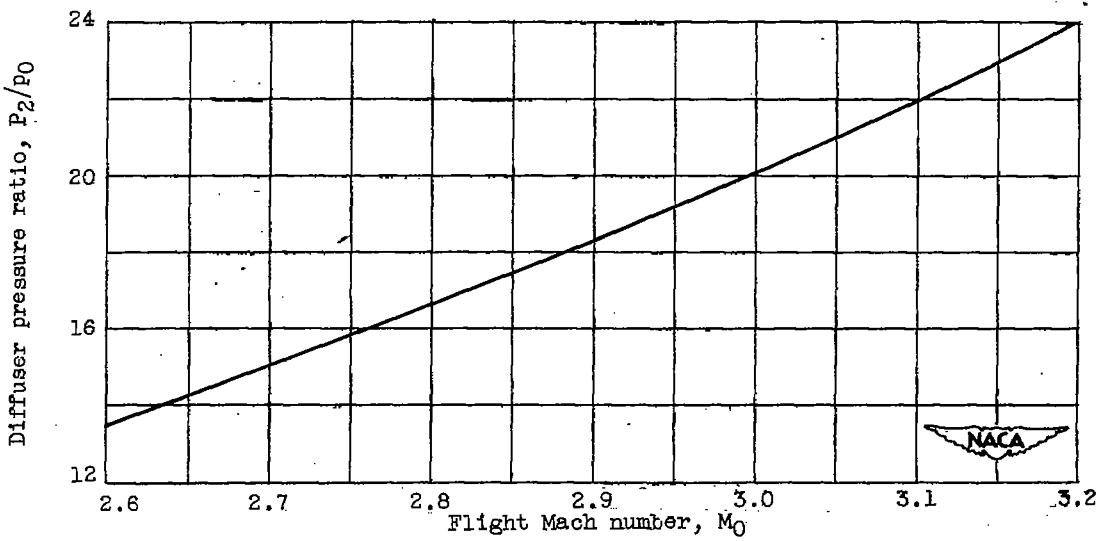


Figure 5. - Required effective fuel flow for critical engine operation as function of flight Mach number.



(a) Diffuser exit Mach number.



(b) Diffuser pressure ratio.

Figure 6. - Required variation of engine variables with flight Mach number for critical engine operation.

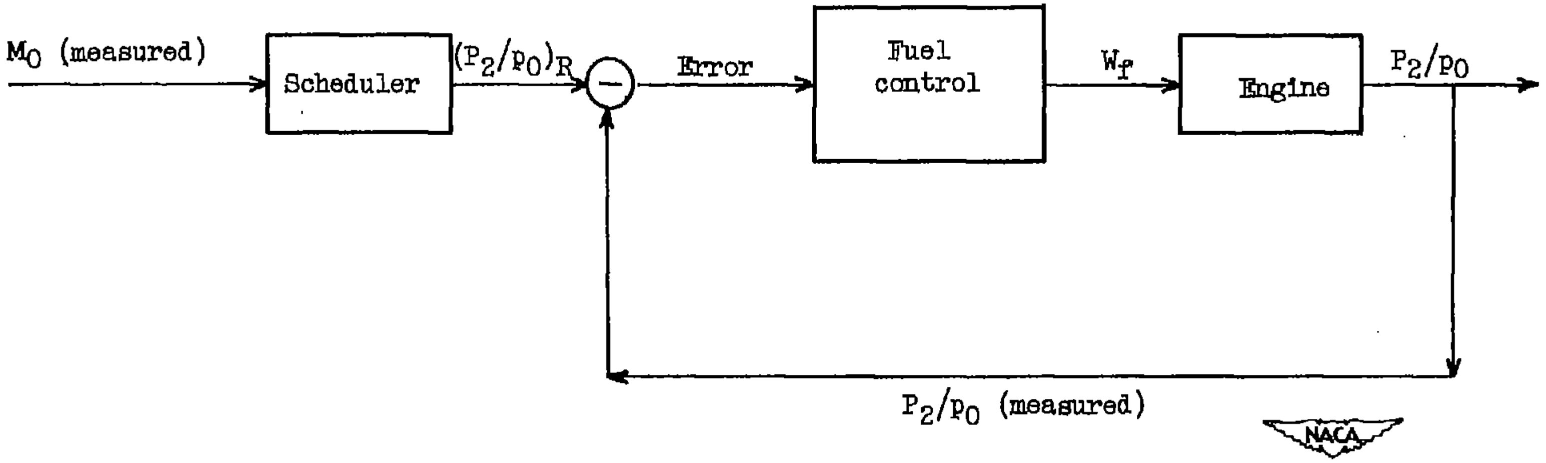

M_0 (measured)
Scheduler
$(P_2/p_0)_R$
−
Error
Fuel control
W_f
Engine
P_2/p_0
P_2/p_0 (measured)
NACA

Figure 7. - Block diagram of control system for maintaining critical engine operation by controlling diffuser pressure ratio.

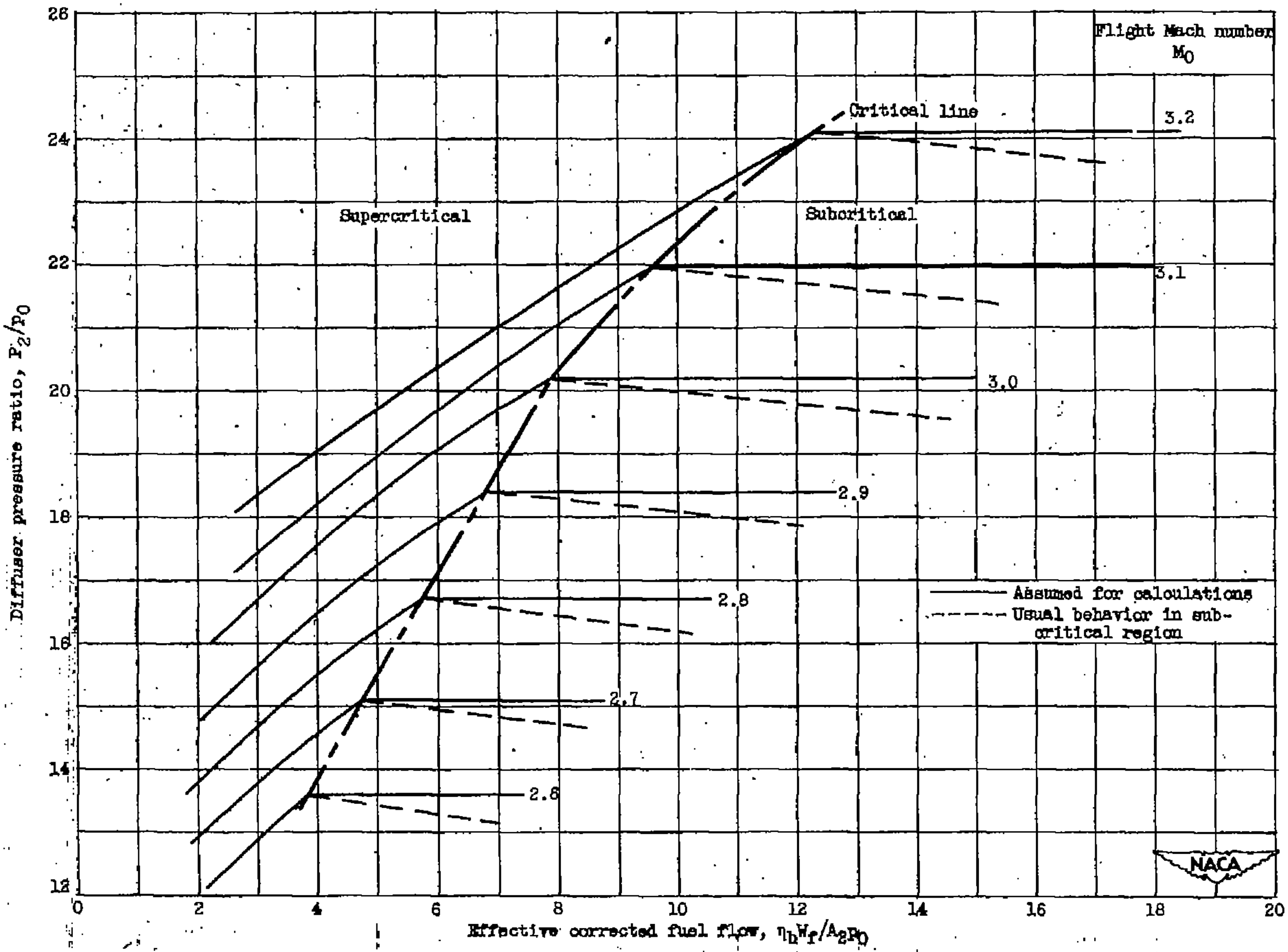


Figure 8. - Variation of diffuser pressure ratio with effective fuel flow at several constant flight Mach numbers.

2570

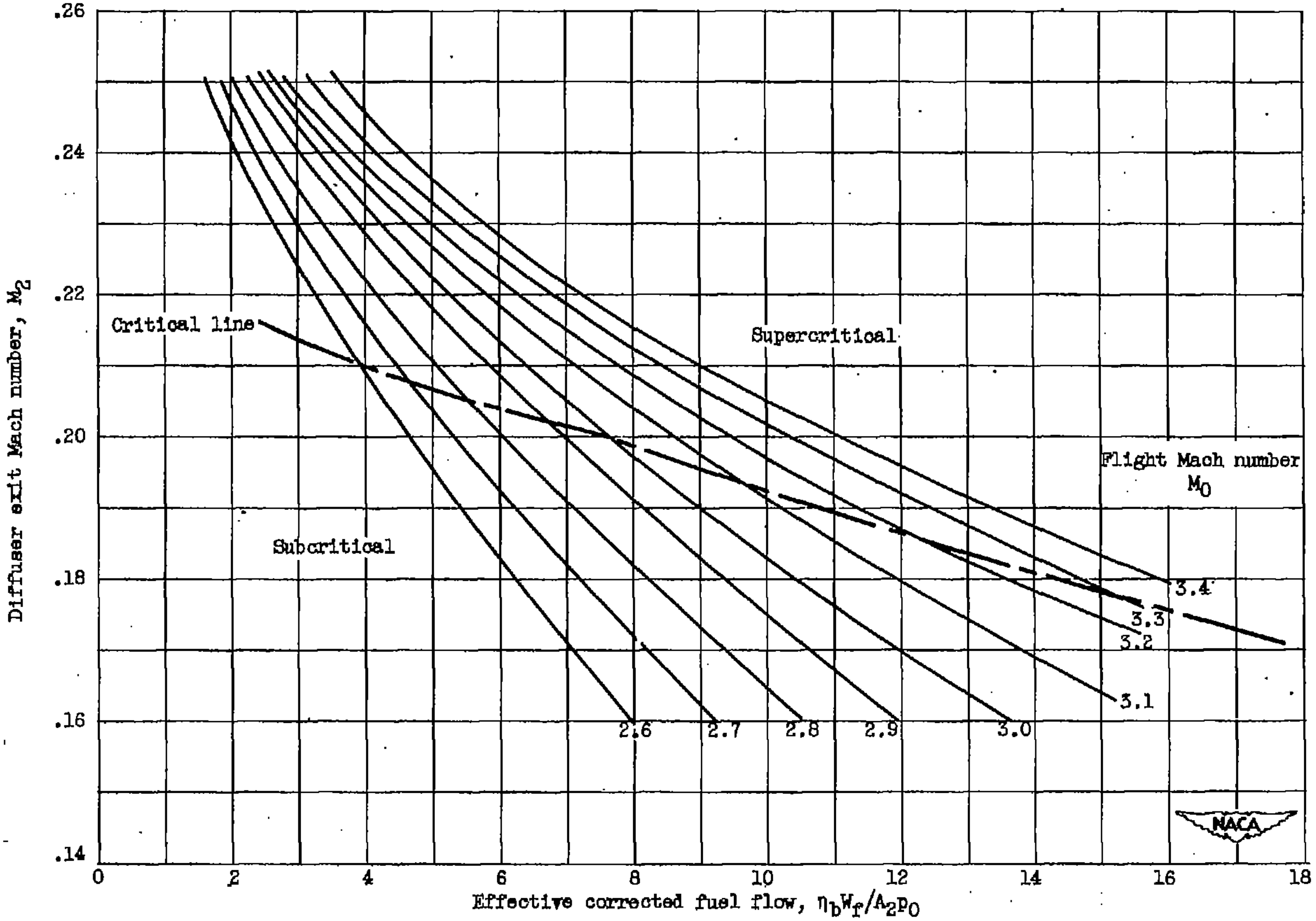
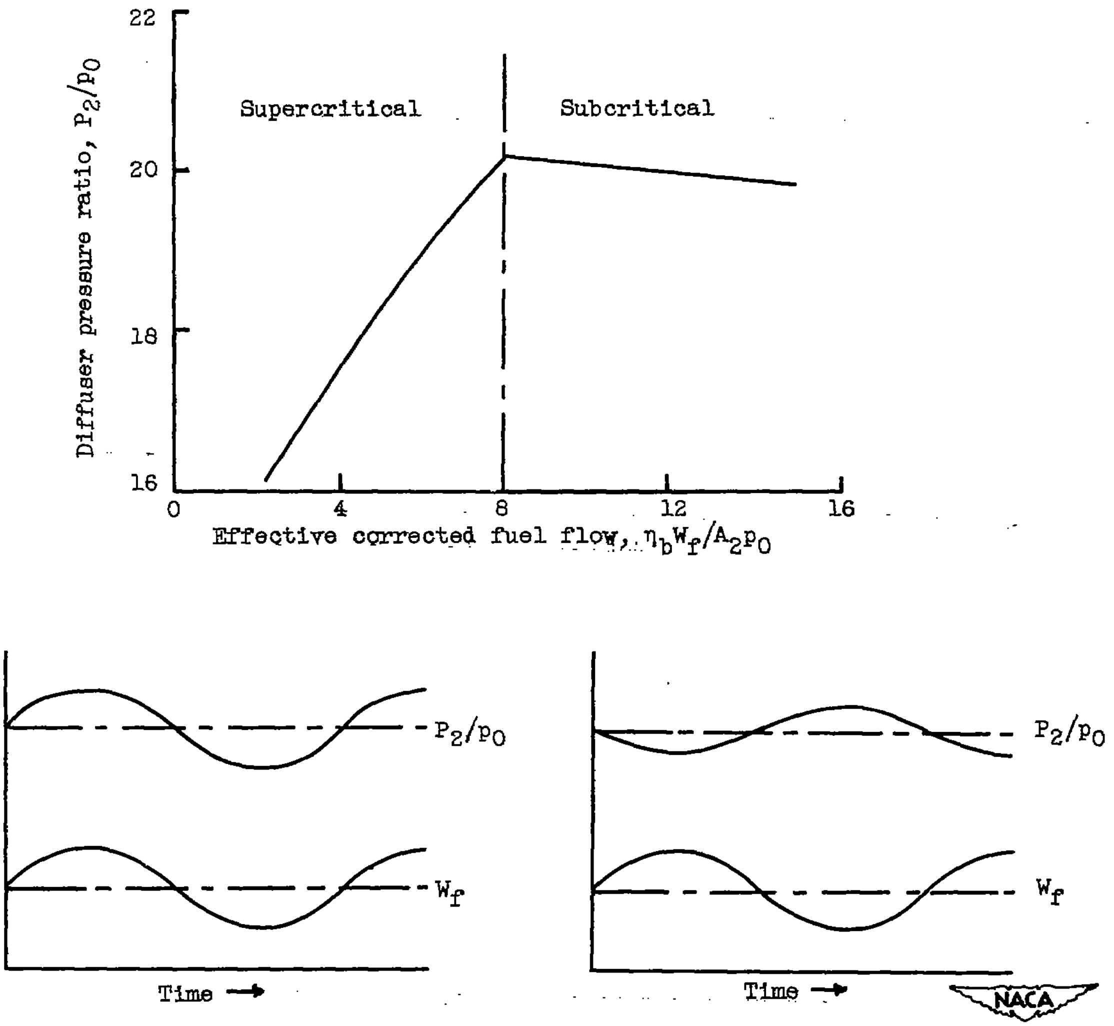


Figure 9. - Variation of diffuser exit Mach number with effective fuel flow at several constant flight Mach numbers.

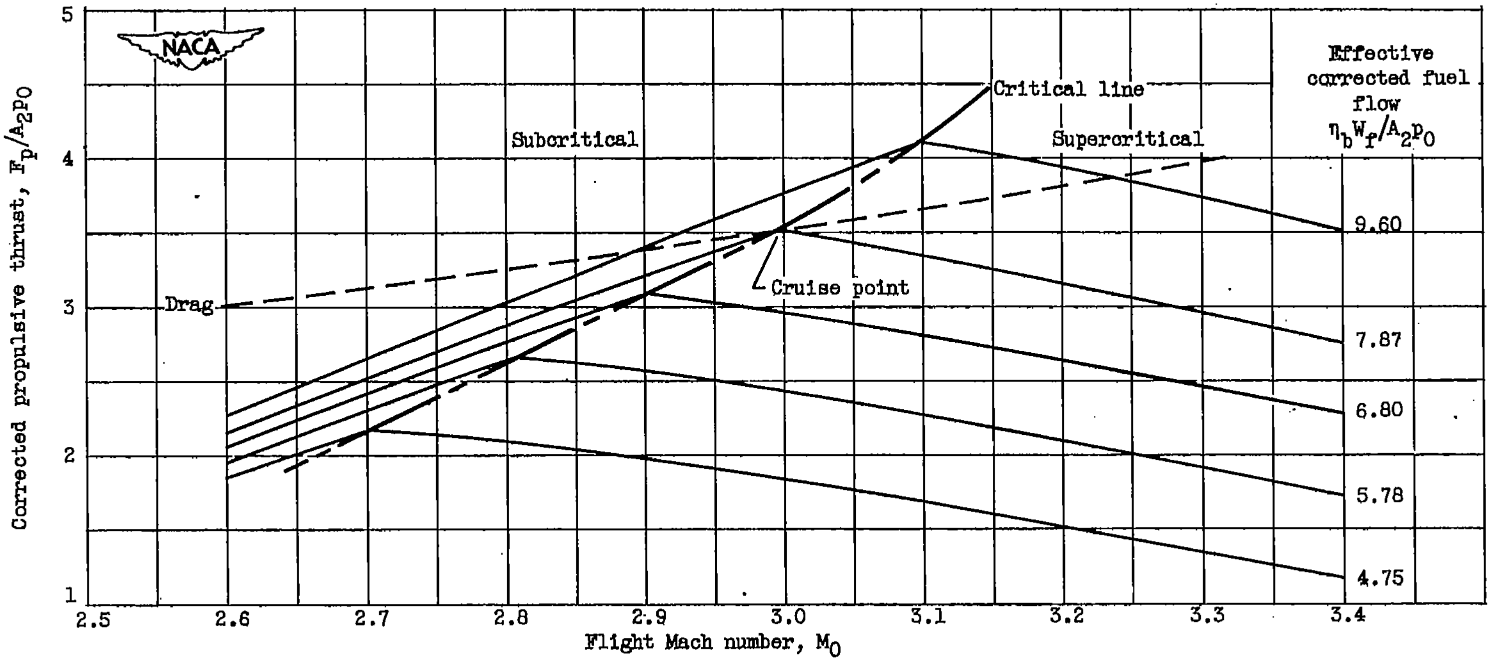
2570



Supercritical region

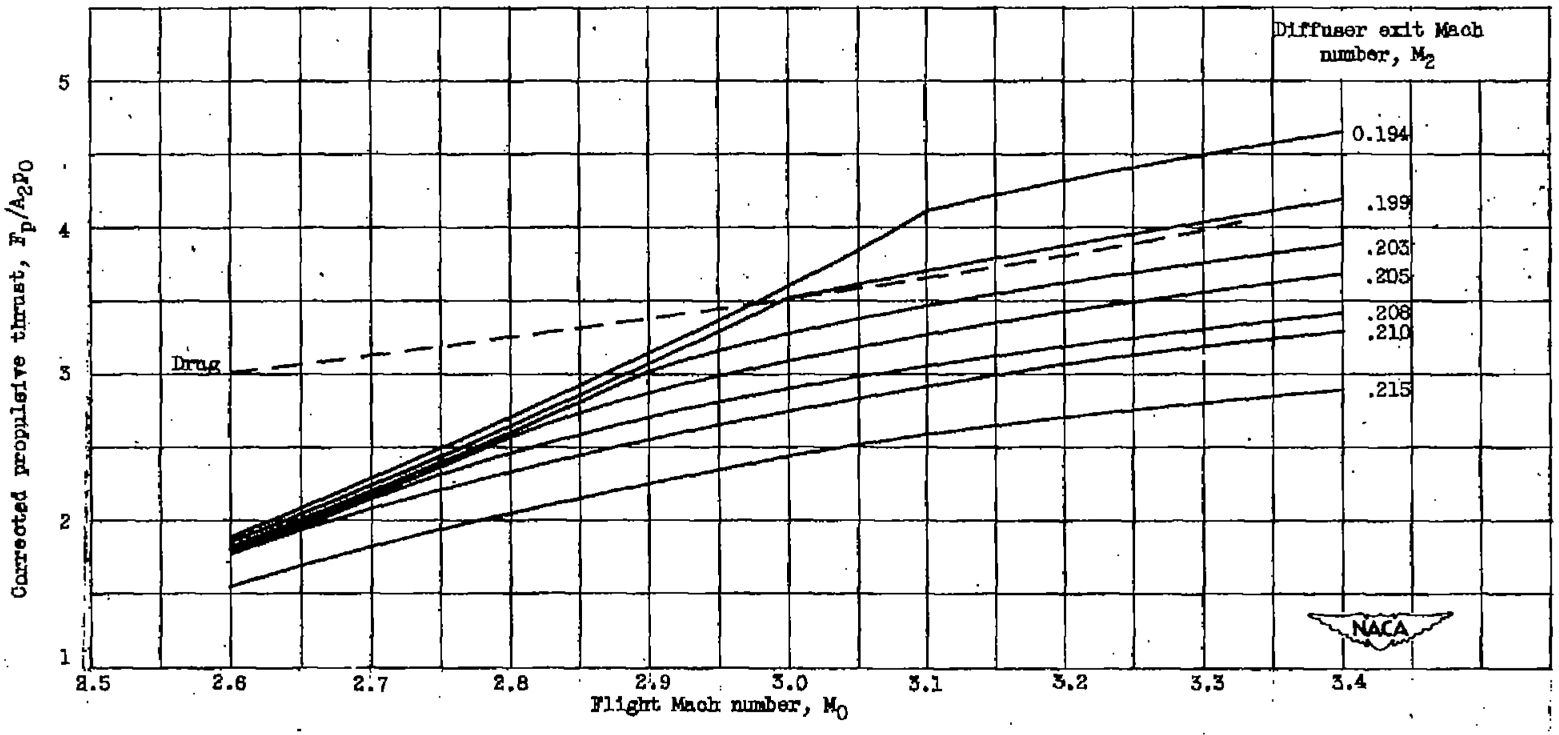
Subcritical region

Figure 10. - Principle of operation of optimizing control system.



(a) Thrust as a function of Mach number for several constant effective corrected fuel flows.

Figure 11. - Ram-jet and missile performance for critical engine operation at cruise point.



(b) Thrust as a function of Mach number for several constant diffuser exit Mach numbers.

Figure 11. - Concluded. Ram-jet and missile performance for critical engine operation at cruise point.

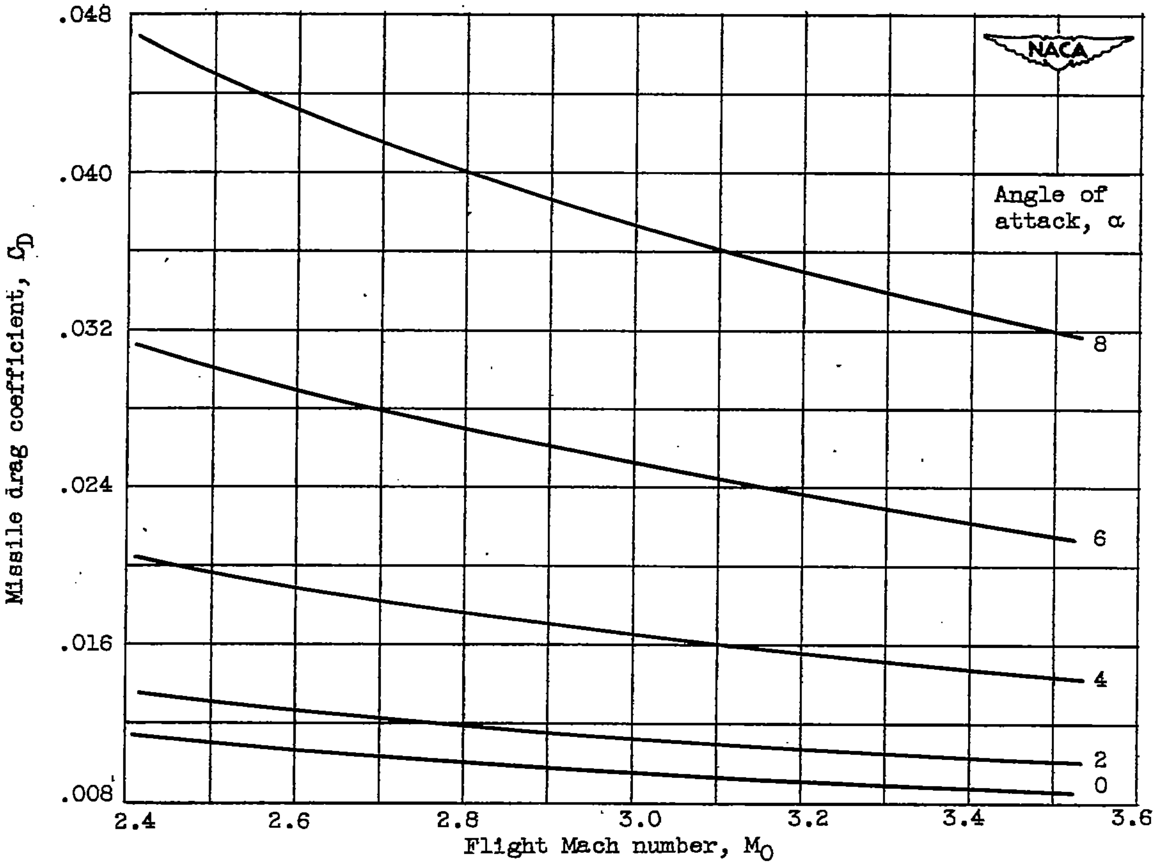


Figure 12. - Drag characteristics of missile. Missile weight, 25,000 pounds; ratio of engine combustion chamber area to wing area, 0.0269; wing loading, 92 pounds per square foot; cruise altitude, 60,000 feet.

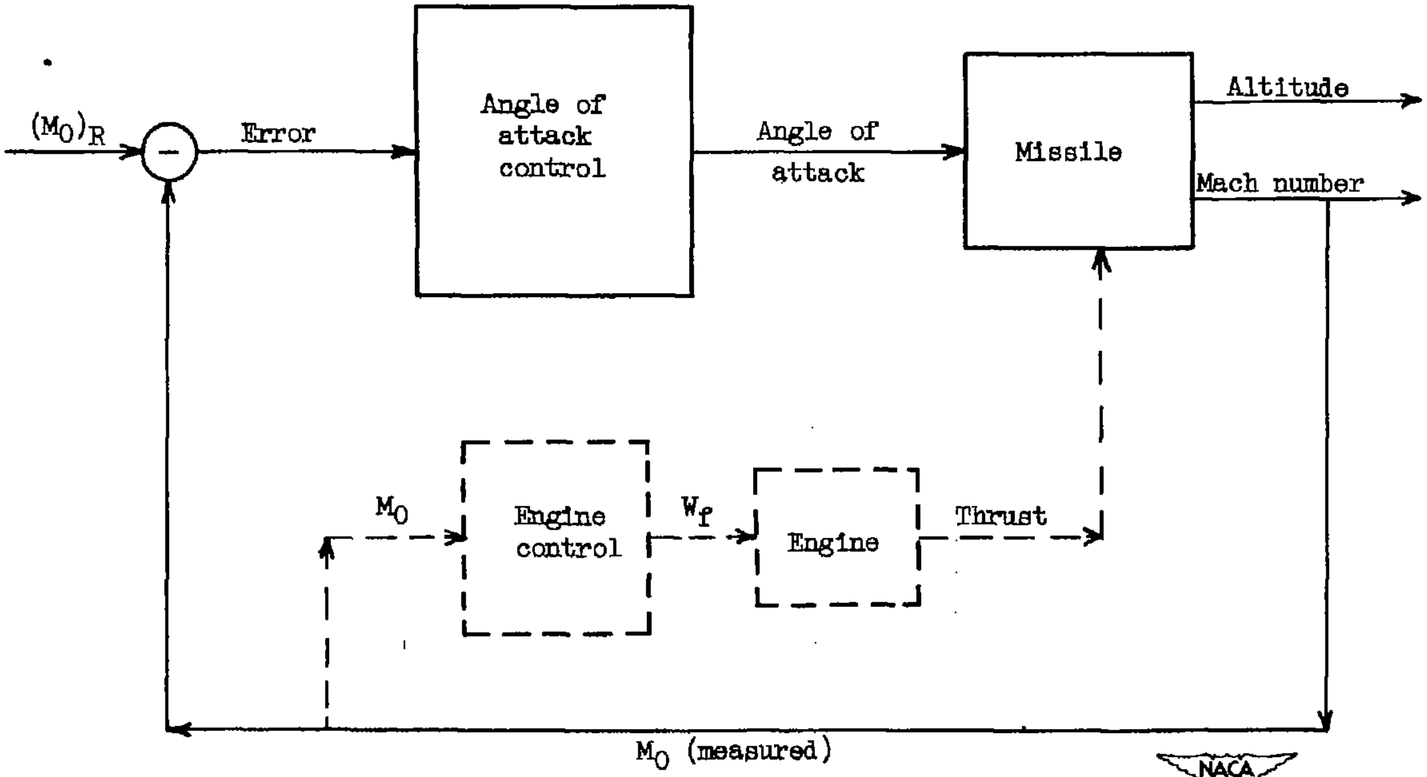

$(M_0)_R$
−
Error
Angle of attack control
Angle of attack
Missile
Altitude
Mach number
M_0
Engine control
W_f
Engine
Thrust
M_0 (measured)
NACA

Figure 13. - Block diagram of control system for stabilization of flight velocity through angle of attack.

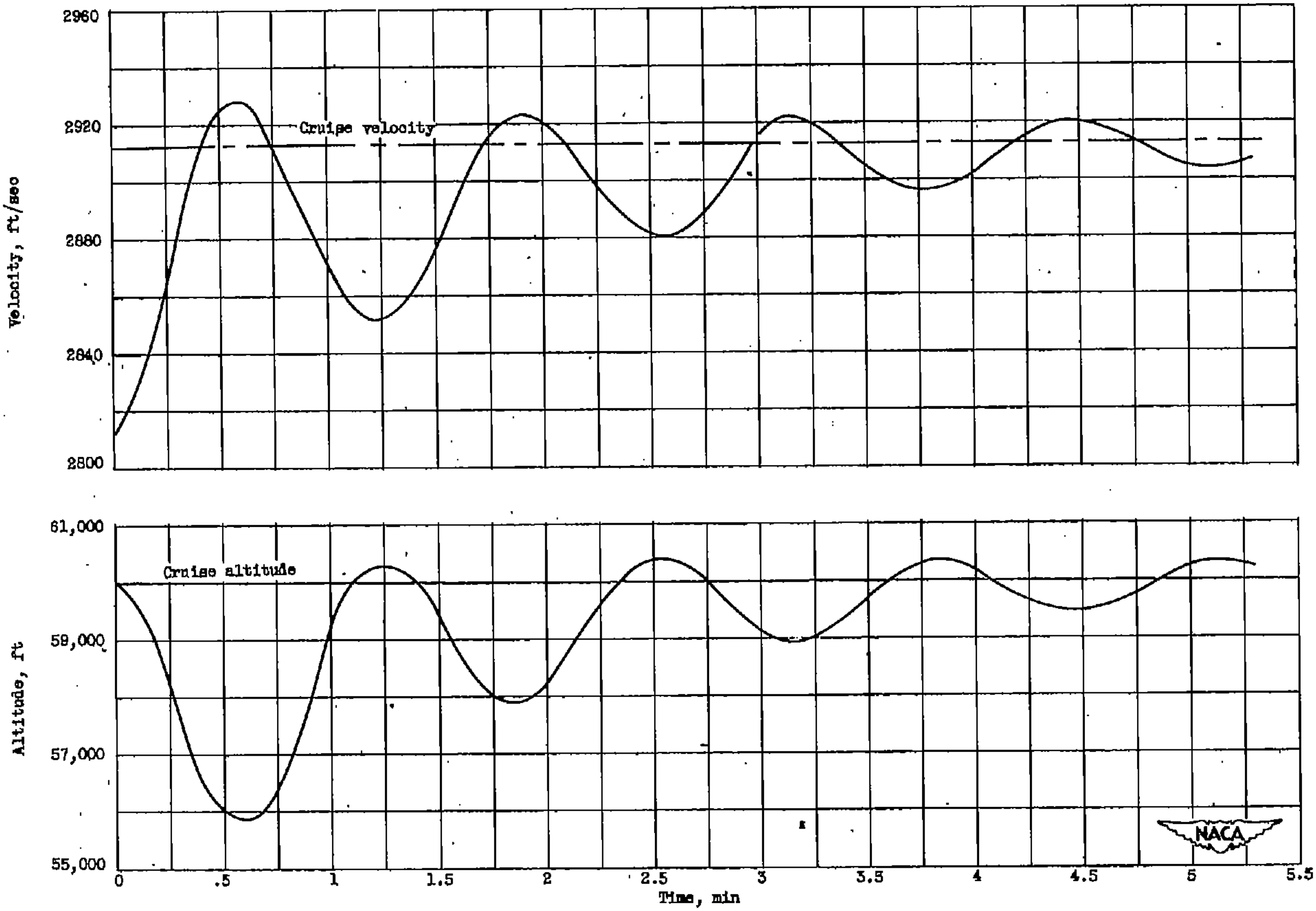


Figure 14. - Response of missile to velocity disturbance with aerodynamic velocity stabilization and critical engine operation.

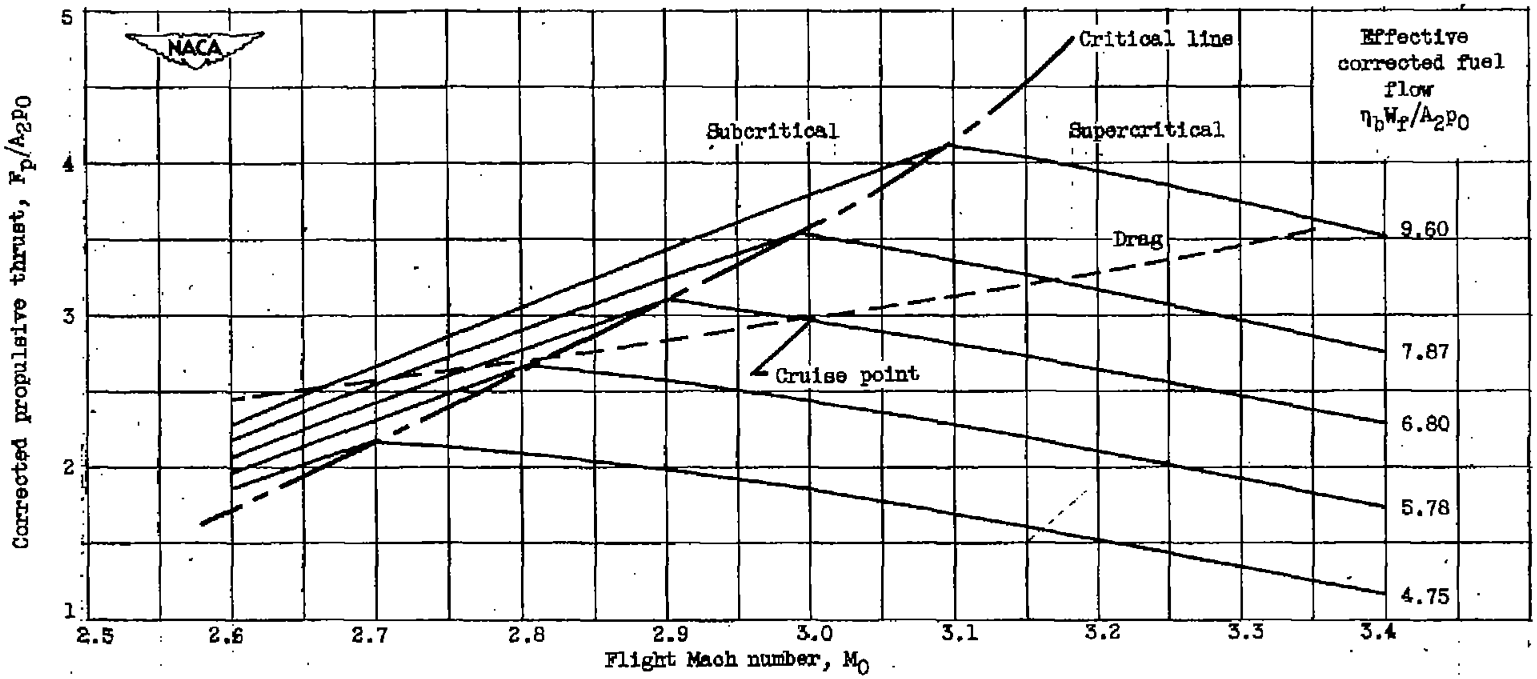


Figure 15. - Ram-jet and missile performance with supercritical engine operation at cruise point.

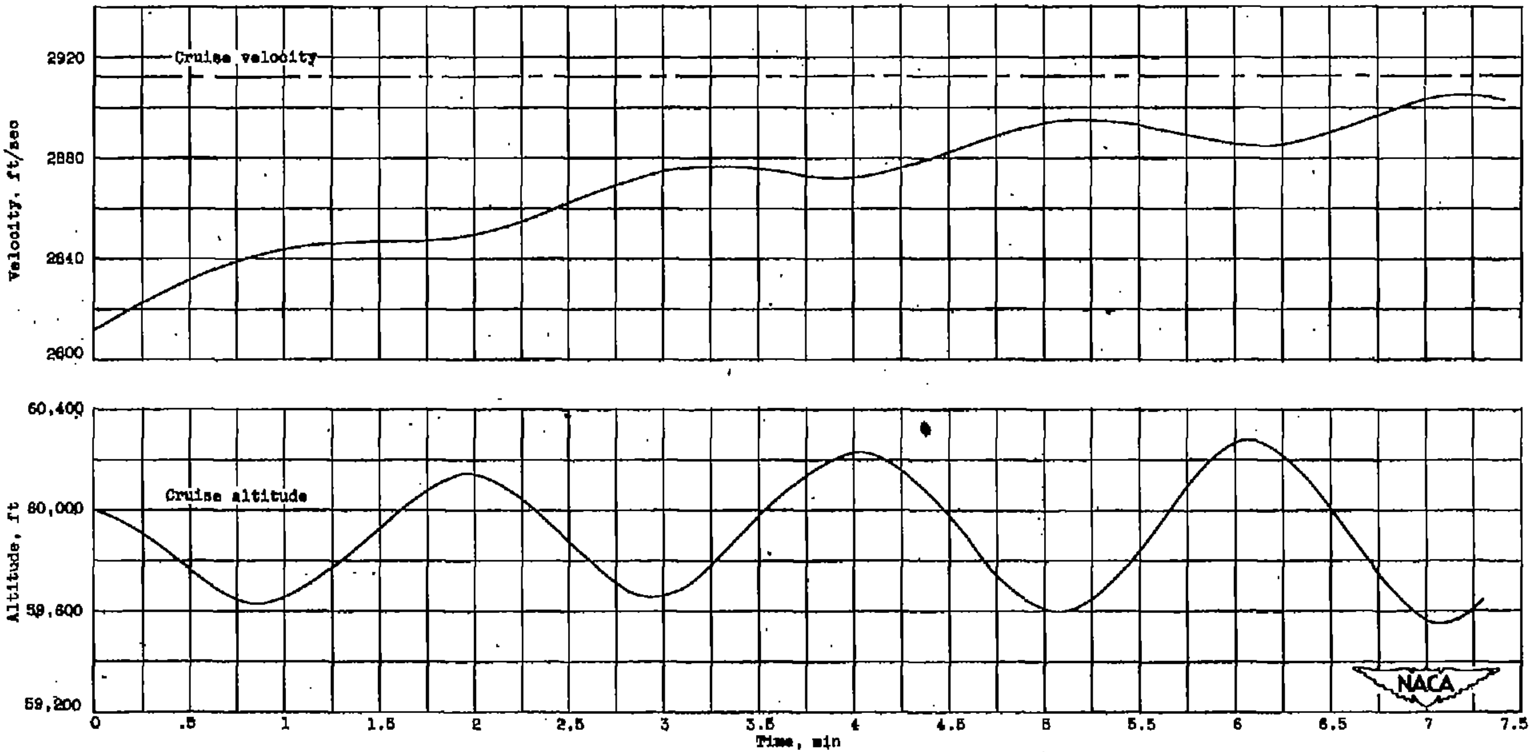


Figure 16. - Response of missile to velocity disturbance with engine operating at constant corrected fuel flow. Missile at constant angle of attack.

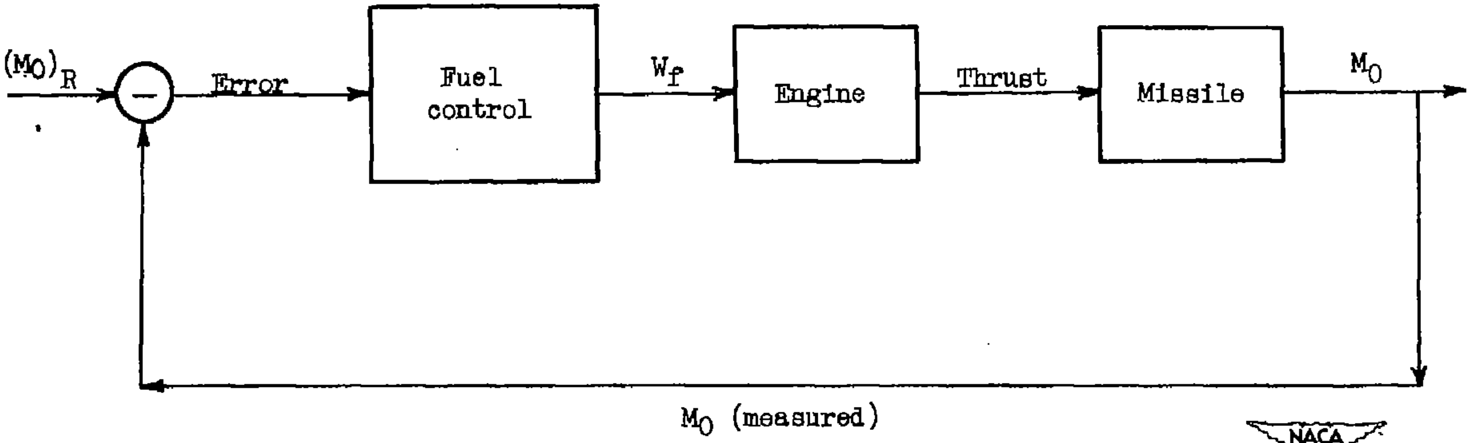

$(M_0)_R$
Error
Fuel control
W_f
Engine
Thrust
Missile
M_0
M_0 (measured)

Figure 17. - Block diagram of control system for stabilization of flight Mach number through engine thrust with supercritical engine operation at cruise point.

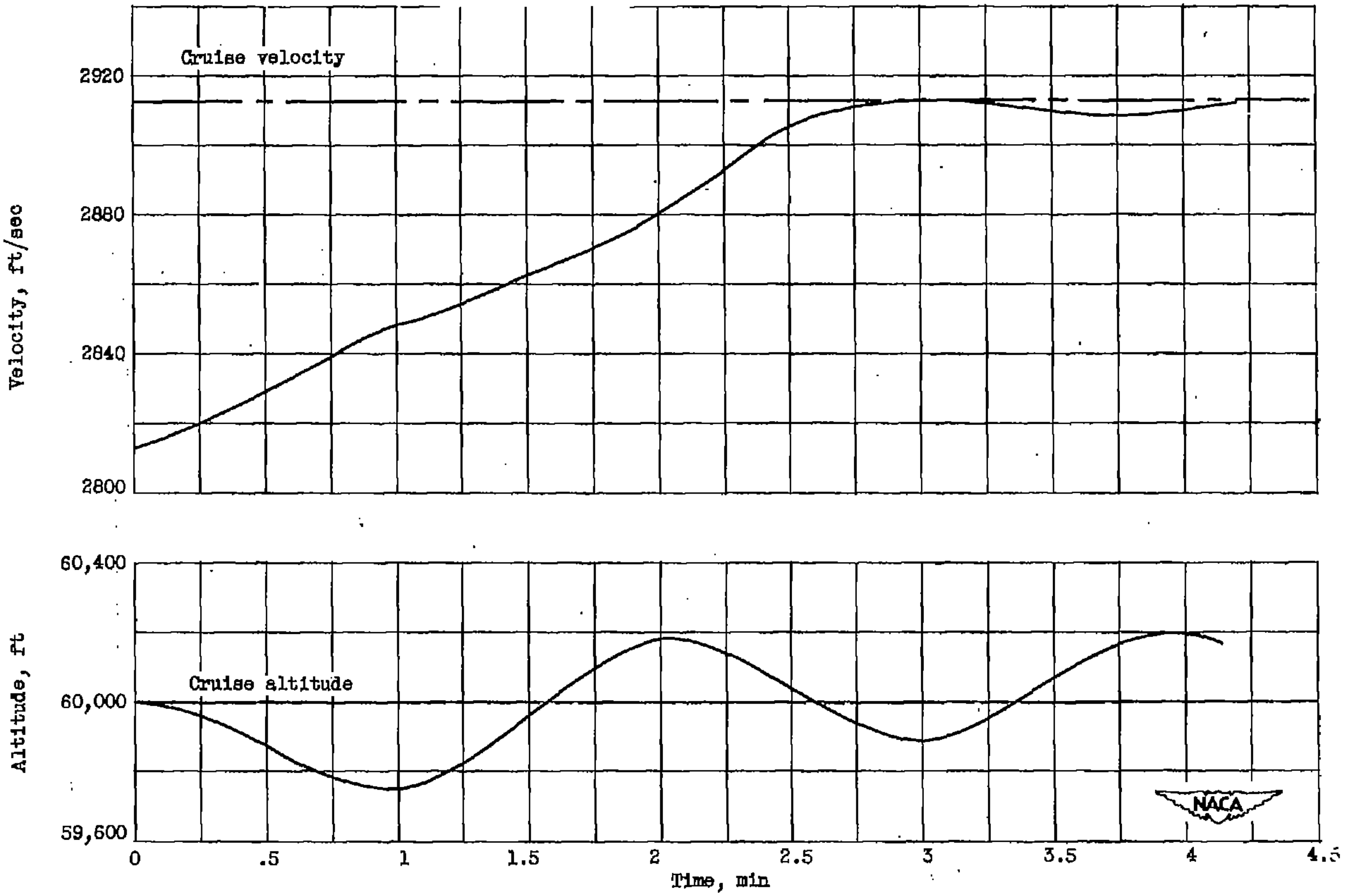


Figure 18. - Response of missile to velocity disturbance with engine thrust cruise velocity control. Missile at constant angle of attack.

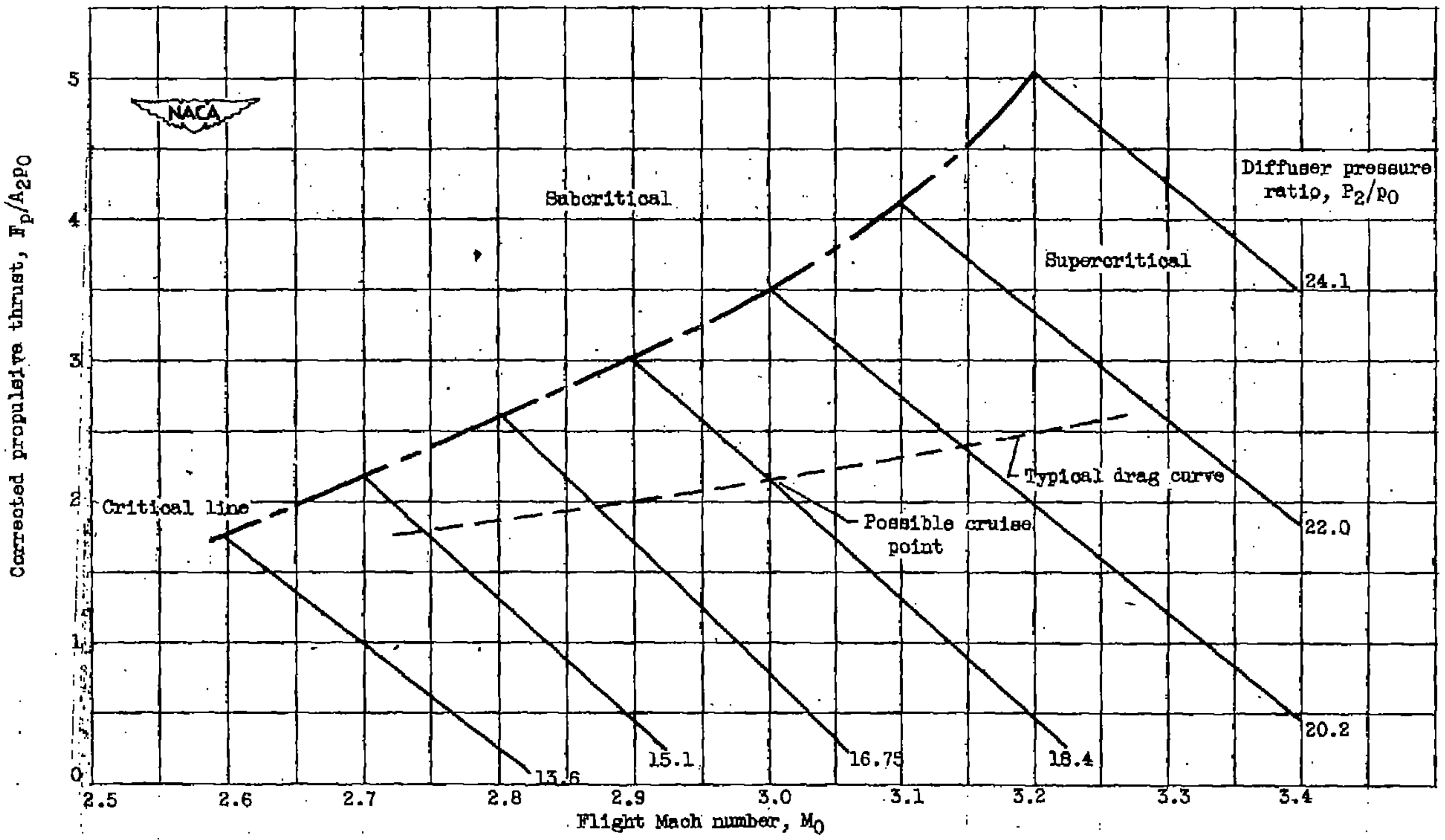


Figure 19. - Performance of ram-jet engine with thrust as function of flight Mach number at constant diffuser pressure ratios.

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